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Selecting Optimal Control Portfolios to Improve Army Aviation Safety

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THESIS

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Sarah E. Shelton

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Abstract

The Army is concerned with maintaining safe operations in light of increasing operational demands. The Army Safety Center's goal, as approved by the Under Secretary of Defense for Acquisitions and Technology, is to reduce accident severity by 50% in the next decade. The Safety Center chartered the Aviation Safety Investment Strategy Team to evaluate accidents to determine their hazards, or contributing conditions, and their controls, or reduction measures. This study specifically targets these force-modernized aircraft: AH-64 Apache, CH/MH-47 Chinook, OH-58D Kiowa Warrior, and UH-60 Black Hawk.

This research takes a look at selecting the best portfolios of controls to minimize aviation accident severity. The accidents are simulated using Monte Carlo techniques. Value-Focused Thinking techniques evaluate the severity of accidents generated by the simulation. The optimization is approached using a knapsack heuristic. Insights into selecting the best sets of controls aid decision makers when determining the portfolios with the best Percent Severity Reduction given budget considerations.

SELECTING OPTIMAL CONTROL PORTFOLIOS TO IMPROVE ARMY AVIATION SAFETY

I. Introduction

By law, The Army is tasked to defend the United States and its territories; support national policies and objectives; and defeat nations responsible for aggression that endanger the peace and security of the United States (33). Accomplishing this goal, while minimizing the cost to its soldiers and to civilians, requires that commanders account for risk when making decisions. Conscientious soldiers and leaders plan for uncertain hazards and seek to eliminate accidents both during times of peace, as well as in combat. Because accidents have historically killed more soldiers than enemy fire, and these losses take their toll on effectiveness, morale and mission-readiness, this issue cannot be ignored. Identifying, assessing, and controlling these risks is the purpose of the *risk management* process (8:1-1,2). The Under-Secretary of Defense for Acquisition and Technology admonished the services to "...achieve a three sigma reduction in Class A accident rate in five years" (13). The Army recognizes the significance of risk management; consequently, the Army relies on the U.S. Army Safety Center (USASC) to maintain the Risk Management Information System, as well as all Army accident information, and evaluate safety-control related issues.

The number of Army aviation mishaps have increased in the past decade, attracting public attention and demanding reasonable solutions. Increasing mission frequency and complexity compounded by decreasing resources may have contributed significantly to this rise in accidents. As the ops-tempo increases, more attention must be directed toward the hazards, the system inadequacies contributing to accidents.

The Army has chosen to address its aviation hazards and controls through the formation of the Aviation Safety Investment Strategy Team (ASIST), a group of safety and aviation experts who analyzed accident investigation information and identified potential hazards and the controls that reduce them (13:1). ASIST proposed a strategy that the

Army Vice Chief of Staff endorsed in April 1999: to reduce the total annual cost of aviation accidents; to reduce the rate of fatal and disabling injuries; and to decrease the accident rate, all by 50% in the next decade. Since the establishment of this strategy, several aircraft have been analyzed and the accident rate for FY00 is 15.9% less than FY99 (34). Nonetheless, meeting the 50% reduction goal across the board is ambitious and requires proper analyses. Risk Management enables the development, fielding, and employment of the Total Army Force. Five steps have been identified to conduct an adequate risk management program (8:2-0):

Step 1: Identify hazards

Step 2: Assess hazards to determine risks

Step 3: Develop controls to make risk decisions

Step 4: Implement controls

Step 5: Supervise and evaluate

ASIST has and will continue to successfully complete steps 1, 2 and 3 for each individual airframe. Step 3 can be broken into two parts, developing the controls and making the risk decisions. The best controls have been suggested by ASIST; this research focuses on the best sets of controls, or portfolios of controls, for the Army to select.

Risk management enhances the decision making process by providing the information required to make informed decisions and to identify control measures in areas that lack specific standards. Supplementing decision making resources, risk management enables a decision maker to provide reasonable, defensible alternatives (8:1-4). The concept of Value-Focused Thinking (VFT) can be brought to bear on this problem, VFT applies the foundational ideas of risk management, addressing first what is important and secondly how to achieve it. A VFT approach puts responsibility for identifying important values in the hands of the leaders; who feel ownership and are able to defend and trust solutions based on their voiced preferences (18:92)

For two years the USASC has seen benefit from AFIT research; Sperling's VFT study and initial value model inspired USASC, in part, to form ASIST (30). Gallan contributed the improved Severity of Losses model to the effort (13). The research described herein

follows on those efforts, addressing the selection of an optimal region for portfolios of controls given certain constraints, such as available budget. A systematic way of evaluating the effectiveness of an individual control or a set of controls was established and accepted, but selecting an optimal set of controls has not been done previously. Using integer programming and a direct-search driven knapsack approach, an optimal region for selecting portfolios of controls is identified. Given the inherent uncertainty, coupled with the combinatorial size of the problem, this heuristic-based method identifies the region for multiple, feasible, reliable results leading to relevant insights into the system, aiding decision makers at the Safety Center.

1.1 Background

Meeting the operational demands of mission readiness while keeping up with technological advances in the evolving environment faced by today's Army requires constant vigilance and effective safety analysis. With a strong foundation in Army Field Manual 100-14, the Army approaches safety from a *risk management* viewpoint. In this context, risk management is a process for making decisions that minimize the risks and severity of danger to soldiers and the mission (8). A hazard is defined as an actual or potential condition that can cause injury, illness, or death of personnel, loss of equipment, property or mission degradation. Severity measures the expected consequence of an event (hazardous incident) in terms of degree of injury, property damage, or other mission impairing factors that could occur. Risk is defined as the chance of a hazard or negative consequence; risk level is expressed in terms of hazard probability and severity (8:G-3). ASIST's hazard taxonomy, a breakdown of what hazards played a part in each recorded accident, improved the accident database by clarifying hazards, controls and identifying their interactions.

Accepted as the model that captured decision-makers' values, the value model quantifies the severity of losses resulting from accidents for 100,000 flying hours for any given set of accident cases. Unlike traditional value-focused thinking where 0 is the least desirable and 1 is highly desirable, the model quantifies *severity,* therefore, a reduction of severity is always preferred. The Severity of Losses values are calculated from accident data on the three most severe classes of accidents: class A, any fatalities or cost over $1

million; class B, severe injuries or cost between $200,000 and $1 million; and class C, minor injuries or cost between $10,000 and $200,000. A Monte Carlo-based bootstrapping simulation returns expected levels of severity reduction for blocks of 100,000 flight hours. The Severity Reduction for a given control is equal to the percent difference between the expected Severity of Losses with no controls applied and the expected Severity of Losses with the selected controls. The portfolio optimization uses these effectiveness levels and the estimated cost for each control to indicate relative performance.

1.2 Problem Statement & Methodology

This research expands the Severity of Losses model to include all ASIST documented aircraft, proposes methodology to incorporate the remaining hazards, and formulates an optimization tool suited for portfolio selection of controls. Hazards are system inadequacies that contribute to an accident occurring or its severity. Controls are measures that counter hazards and reduce the occurrence or severity of accidents. The focus of this research is on presenting a methodology and a working prototype to integrate multiple systems; the USASC leadership can benefit from the latter insights by implementing these methods in all aspects of safety that are categorized into controls and hazards. Figure 1.1 shows how a single airframe fits into the hierarchy of loss contribution. A UH-60 accident contributes to the overall accident rate in rotary wing aircraft, in Army aviation, and the Army as a whole. The goal is to reduce accident severity at the Army level.

The primary aspects of the research are developed separately: the multiattribute value hierarchy, the bootstrap statistics using Monte Carlo simulation, and the portfolio optimization model. The multiattribute value hierarchy, based on the Army's Risk Management field manual, is modified using Value-Focused Thinking methods first proposed by Keeney and expanded by Kirkwood. As a solid framework has already been established by Sperling and Gallan, this expanded hierarchy focuses on assessing Army level versus battalion level values and their weights. This new Severity of Losses model integrates additional aircraft as well as identifies and analyzes hazards consistently, providing necessary insights to senior leadership. The results influence the selection of portfolios of controls that provide the most reduction in losses for given budget levels.

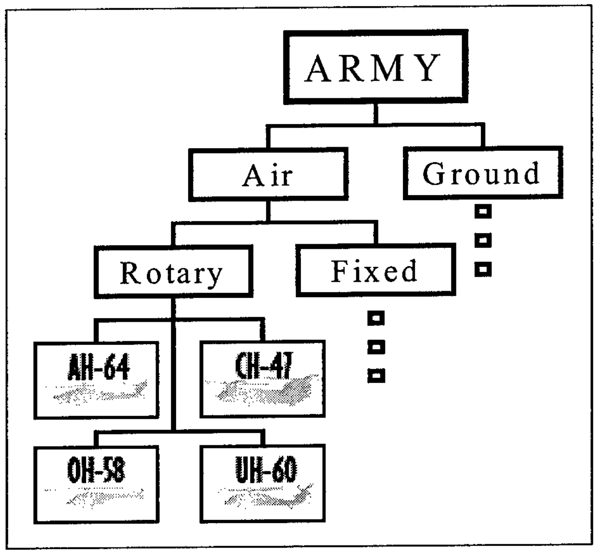

Figure 1.1 Scope of the Study

Assuming the validity of the Severity of Losses model developed by Gallan, the first step in developing a robust, expanded model was to integrate the new accident data into a single data set. Developing the Simulation to account for multiple systems, in this case airframes, involved updating measure ranges to include new observations. This study considers the intent and expected use of this tool by decision makers when basing all severity scores on the preferences of experts and leadership.

Once the model was developed to produce an expected reduction in severity for any given trial portfolio, the search for a best portfolio began. Portfolio selection may be approached many different ways. Traditionally, decision analysts approach portfolio selection, also known as resource allocation, by ratio methods. Another reasonable approach to this mathematical program was found in the knapsack problem, which also accounts for resources (22). Exploration of derivative-free optimization methods fall into a category called direct search methods. These interesting and applicable algorithms efficiently search regions proceeding to new points based upon improvement in an observed objective value (32).

Focusing on the Army's goal, each portfolio may contain a control from any system under study. If a specific portfolio can eliminate all of the accidents for one aircraft,

the Army's overall accident rate may drop only slightly. The Army desires to reduce the accident severity across the board, not just for one aircraft. Consequently, all aircraft cases must be aggregated and analyzed, their hazards noted, and controls selected to achieve a significant drop in losses, and ultimately, the overall Army accident severity. The integrated methodology addressed in this study provides an acceptable level of reduction in losses for the Army while it remains within a designated budget limitation.

The data used comes directly from the ASIST database managed by the U.S. Army Safety Center, Fort Rucker, AL. ASIST, the Aviation Safety Investment Strategy Team, developed the hazard taxonomy and controls. This research takes and develops an optimization strategy for the aircraft, as a whole, that ASIST has analyzed to date. This includes the UH-60 Black Hawk, AH-64 Apache, CH-47D Chinook, and OH-58D Kiowa Warrior. Due to the massive amount of excellent analysis done by ASIST, all of the data needed for this research is available and has been provided by USASC/ORSA. Incorporating this data and implementing the methodology utilizes several software packages: Microsoft Access, Microsoft Excel, Frontline Premium Solver Platform, and Palisade's @RISK. The methodology integrates these packages to make use of specific capabilities of each.

1.3 An Overview of Subsequent Chapters

This research combines decision analysis, simulation, and optimization to yield a specialized methodology providing unique insights and practical applications. Chapter Two discusses the literature pertinent to this study including decision analysis methods, Monte Carlo simulation techniques, portfolio selection, integer programming, and simulation optimization. The complete methodology is contained in Chapter Three; it implements the data on the multiple airframes and searches for the best portfolios of controls to meet the goal of 50% reduction in severity. Chapter Four discusses the results of applying the ASIST data to the methodology and also provides insight into the interactions driving portfolio selection. In addition, sensitivity analysis of the results provides significant insights to whether high levels of accident reduction are possible, reasonable, or affordable. Final recommendations, insights and conclusions appear in Chapter Five; this discussion suggests

improvements to the data, and recommends guidelines for selecting tractable portfolios. This thesis effort concludes with a discussion of recommendations to be made for the Army, the Air Force, and the FAA with regards to this study.

II. Literature Review

2.1 Introduction

This chapter first introduces the reader to decision analysis and optimization techniques. The discussion on decision analysis addresses Value-Focused Thinking. A Monte Carlo simulation application of the bootstrap method is explained. Finally, an introduction to mathematical programming follows, discussing integer programming, the knapsack heuristic, and direct search methods, showing how they can be combined with the simulation model.

2.2 Decision Analysis

2.2.1 Foundational Concepts. Decision analysis is a prescriptive approach to help rational people make difficult decisions (4:3). This methodology helps the decision maker to model the decision area and to integrate the structure of the problem with their preferences and beliefs. When facing a decision, every decision maker tries to choose the alternative that will achieve the best outcome. An outcome is the product of the decision made and the chance involved given an uncertain payoff, or future outcome. Because the uncertainty cannot be controlled, rigorous calculations and analyses are conducted to submit a thorough foundation for making a good decision. In-depth studies may seem unnecessary for some problems; easy decisions need not be subject to this rigorous analysis. The intent of decision analysis techniques is to provide a framework for approaching *hard* decisions (4:3).

Decision analysis fundamentally aids a decision-maker by providing insight into the uncertainties, trade-offs, and objectives of a problem (4:4). At most, decision analysis provides a recommended course of action, but, in no way takes the authority of decision making from the leadership. It does not compete with a decision-maker's intuition or take away their obligation to decide, rather, it is simply a valuable tool to help them understand their problem more clearly and make a better decision (4:4).

An analysis of this type is not purely objective. Decision analysis *requires* personal input from experts. These subjective judgements are a key ingredient for making good

decisions. Understanding human inconsistencies is necessary to carefully apply good techniques and recommend improved decisions (4:5).

For a decision-maker to stand behind a decision of theirs, they must understand the decision analysis process and trust the underlying values and objectives they have provided. The first step in this process is to clearly define the problem. Although this may seem to be a simple task, a superficial problem, or the question initially asked, may mask the fundamental issue and may make finding a clear definition difficult. The following steps describe a method to help clarify decisions using Value-Focused Thinking.

2.2.2 Value-Focused Thinking. Value-focused thinking techniques boast extensive use across the public and private sectors of our economy. Focusing attention on the important objectives of a decision maker and not the possible alternatives, value-focused thinking (VFT) techniques provide clear methods to evaluate alternatives. The development of value models by area experts and knowledgeable decision makers give a consistent standard by which to measure all alternatives (18). A formal diagram, or model, represents at different tiers the values that are important to a decision maker with regard to the particular issue at hand. Its purpose is to determine how to measure significant issues and evaluate alternatives with respect to the "important things" (19:11).

The multiple objective value model (as in Figure 2.1) consists of a fundamental objective, evaluation considerations, objectives, and evaluation measures. The fundamental objective simply describes the overarching goal. An example may be selecting a new car. The evaluation measures, or criteria, are the important factors that explain what is meant specifically by the fundamental objective. For this example, the evaluation measures could be *speed*, *safety*, and *style*. Objectives specify a preference for the evaluation considerations. A faster, safer, more sleek design is most desirable to some, while a moderate speed vehicle that is very safe and slightly "boxy" might be the most desirable to others. As is obvious with the example, the objectives are dependent upon the decision maker. Sub-objectives will likely exist for more detailed models. Evaluation measures constitute the lowest tier of the value model. These measures scale the degree to which an alternative attains desirable objectives (19:12). When navigating through the tiers, moving to a lower

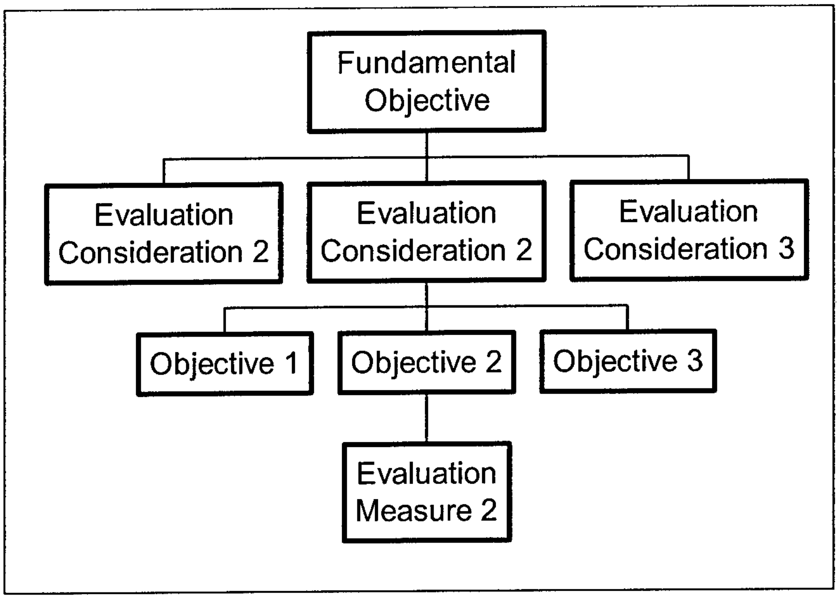

Figure 2.1 Multiple-Objective Value Model

tier requires answering "why is this (the current objective) important?" Moving to higher tiers answers the question "what do you mean by that (the current lower measure)?" (27).

The Value Model consists of a qualitative part and a quantitative part. The qualitative part is the value hierarchy, similar to the general picture in Figure 2.1. Information that makes up the values, objectives, and measures comes directly from field experts, documents and doctrine, shareholders in the decision process, and any individuals knowledgeable about and interested in the decision. The quantitative part consists of the scoring functions used at the evaluation measure tier and the weights specified for all tiers the model.

Value hierarchies must meet certain criteria: they must be *complete*, *nonredundant*, and *independent*. The first two properties are often referred to as *mutually exclusive* and *collectively exhaustive*. When two objectives are mutually exclusive, they address unique items of importance, without overlap. Likewise, a set of collectively exhaustive objectives ensure coverage of all relevant issues of importance. The evaluation measures must adhere to the property of *independence*. This means that the value of a certain level of one measure must not be dependent on the level of a different evaluation measure (27:2.6).

Each evaluation measure uses data to evaluate how well each alternative performs with respect to the objective; the analyst must decide, with the decision makers, what data is most representative of the objectives being attained. Scales for evaluation measures are categorized as *natural* or *constructed* to identify how clearly the scale may be interpreted, and the measures are also categorized as *direct* or *proxy* to identify how the scale represents the objective. Identifying types of scoring functions enables decision makers and analysts to simply explain how the data represents the objective. The following specific descriptions and examples illustrate the most desirable types of scales for evaluation measures (19:24).

A *natural* scale is commonly used and is easily interpreted by most everyone. Profit in dollars is a natural scale that may be used to evaluate a business decision. A *constructed* scale is often developed with a certain decision in mind; often characterized by categories, a constructed scale measures the attainment of a particular alternative. This type of scale may be appropriate where a natural scale is infeasible. The performance evaluation categories of a selected group are constructed scales (19:24)(27:2.25).

The *direct* scale measures the degree of attainment of the objective. A *proxy* scale measures the degree of attainment of an associated objective. For example, "probability of kill" directly evaluates an objective *Kill Likelihood*. Whereas, "student grades" are a proxy measure for the attainment of the associated objective of student learning (19:24) (27:2.25).

Table 2.1 Classification of evaluation measures

	Natural	Constructed
Direct	1	2
Proxy	3	4

These combinations of classification methods for the evaluation measures create four possible combinations of scale types, and as the analyst seeks obtain the most accurate and representative hard data available, the categories are ranked by preference in Table 2.1. Natural-proxy scales, preference 3, and natural-direct scales, preference 1, have the benefit of a pre-established axis for measurement. Any constructed scale takes significant

time to establish and verify. Selection of appropriate scales always depends on the most fitting measure, however, it may also depend on the data available to the decision maker.

After identifying the scale, a value function quantifies each observation's attainment of the *objective* on a 0-1 scale. The most desirable level receives a value of 1.0 and the least desirable level receives a 0.0 value. The intermediate values are determined by asking the preferences of the decision maker and obtaining uncertainties inherent in the measure. Every evaluation measure has an important part in the final evaluation of the fundamental objective and each step of the process must be carefully evaluated and documented to ensure future users are able to unambiguously assign consistent values (19:28).

The final step in developing a value hierarchy requires quantifying the relative importance of objectives occupying the same tier. Experts recommend ranking and comparing the extremes of evaluation measure scales using *swing weighting* (19:64). This method consistently evaluates the relative importance between increments in value, assuming some preference between objectives. Finally, once alternatives are scored with regard to the fundamental objective, varying the weights reveal the sensitivity and provide insight about the alternatives.

2.3 Simulation Techniques

2.3.1 The Bootstrap Method. First published by Efron in 1979, the bootstrap method is a powerful non-parametric method for obtaining an estimator's accuracy when data is limited, specifically providing reliable measures of uncertainty such as standard errors and confidence intervals. Bootstrapping empirically generates a statistic's distribution. Using a Monte-Carlo resampling simulation, the bootstrapping technique statistically samples and analyzes data from an unknown distribution, generating the statistic's distribution (36). Standard error is the most common measure of an estimator's accuracy; this measure is often difficult to obtain due to unobservable samples. A sound approximation of the numerical value of $se_F(\theta^*)$ is computationally possible using the bootstrap method (11:47). The name for the bootstrap method originates from the fictional Baron Munchausen, who, after falling to the bottom of a lake, pulled himself out by his bootstraps. The name helps explain the technique; sampling from the collected data and evaluating the

resulting data sets reduces the sampling error (5:3). As with any estimation, the standard error must be calculated, and the smallest error possible is desired.

To gather important statistics from empirical data, the bootstrap method draws random samples, with replacement, to generate those statistics. This method is particularly useful in situations where no well-defined probability distribution is available. The primary advantages of using this method include its simplicity of explanation and calculation, and the absence of distribution assumptions (11:160). The most significant drawing factor for this research is that for complex situations, as with computationally difficult statistics, Monte Carlo samples may be used to approximate the parameters of interest, namely the mean and its corresponding confidence interval (11:1).

While only a small number of bootstrap replications may be required to estimate the standard error, an additional factor of ten replications is necessary to calculate the bootstrap confidence interval (11:15, 52). Since the re-sampling is from from limited data, the key sensitivities of the bootstrap method are similar to all statistical analyses; particular attention must be paid to confirm correct experimental design, data analysis, and especially correct presentation of conclusions (5:4).

2.3.2 Monte Carlo Simulation. Monte Carlo simulation generates the input statistics in a way that is analogous to actual observations. The Monte Carlo samples from this simulation are used for the bootstrap data samples. Often this ability to systematically vary inputs provides valuable information that observations cannot supply. The goal of Monte Carlo simulation is to exploit theoretical mathematics while avoiding the risks of large variance by replacing theory with actual experimental data where applicable (15:4). Random input selections, when carefully managed, can aid in decreasing the associated variance within the system. One approach is to use real observations and data wherever practical. However, this introduces another limitation: the study infers that all possible occurrences are in the database, a fact often known to be incorrect. The output statistics associated with this simulation, as well as any, are only as accurate as the observational data upon which it is based (15:4).

The expected outcome of a value model that contains uncertainty can be estimated using Monte Carlo simulation. Random number generation is the enabler of this tool. Every uncertainty that influences the system has an underlying probability distribution function. By drawing random numbers from these distributions, the data manipulation within the program generates a single-value outcome. Repeating this trial n independent times gives reliable data from which to statistically analyze and draw conclusions (4).

Currently, many tools exist to implement Monte Carlo simulation; the application of choice for this study is @RISK, add-in software by Palisade for Microsoft Excel. This package allows the user to uniquely model any system with built-in probability distributions. As a simulation progresses, each iteration generates new possible outcomes. @RISK keeps track of the output values and generates a distribution of possible outcomes from all the observations. This distribution is created by taking all the possible output values, analyzing them and calculating statistics on their minimum-maximum range (25:51). It reports the summary statistics upon termination of the experiment. Microsoft Excel and Palisade's @RISK enable the Severity of Losses calculations and projections in this project.

2.3.3 Probability Theory. Useful simulations and statistical inferences rely on correct inputs. Monte Carlo simulation uses uniformly distributed random variables as the foundation for its application. In addition, a specific input may be based on empirical data, entering the system in the form of random number variates from a specified distribution. To return an integer value, the set of possible distributions becomes significantly smaller. Often in practice, interarrival rates are represented using an exponential distribution (20:390).

Poisson processes maintain properties that account for random occurrences over time (20:390). Because it can be shown that interarrival, or inter-occurrence, rates of accidents follow an exponential distribution, the next appropriate step in modeling accidents for a given time period is to use a Poisson process. A stochastic process $\{N(t), t \geq 0)\}$ may be labeled a Poisson process if it adheres to the following properties (11:160):

1. Events occur one at a time.

2. The number of events occurring in any interval $(t, t+s)$, is independent of the number of events occurring before time t.

3. The distribution of the number of events occurring in any interval of length s is independent of what time t the interval begins.

An assessment of how accident occurrences meet these properties appears in Chapter Three.

2.3.4 Applications of Simulation Techniques in Current Literature. Utilizing simulation in conjunction with the bootstrap method is explored in work by Hurry, in an application determining the impact of Programmed Depot Maintenance on weapon system availability. His work supports independent sampling, with replacement, from empirical distributions. This analysis produced estimates on time to failure and downtime following a failure; the results of this study confirmed conclusions from previous analyses (17).

2.4 Optimization Techniques

Although there are accepted portfolio selection heuristics within the decision analysis community, the most robust methods recommend the use of 0-1 linear programming for finding portfolios with the highest value (19:207). These resource allocation methods use ratios, cumulative cost, or cumulative benefit to select variables. The available heuristics provide acceptable, reasonable solutions for extremely small sets, or large sets where precision is not necessary. With the expanding capabilities of hardware and software, however, larger and more complicated integer programs are now significantly easier to solve than when these methods were first discovered and used.

There are several types of formulation methods that utilize integer programming techniques. Seeking to find an optimal solution, simplicity drives the program formulation. If the problem proves to be NP-hard with intractable solutions, then appropriate heuristics may be used to approximately solve the problem. This section addresses the pertinent literature describing techniques used to optimize problems with characteristics similar to the portfolio selection problem addressed in this study.

2.4.1 Knapsack Problems. This type of problem is of particular interest because it suggests attaining the most benefit possible by selecting items that, given a limited amount of space, each contribute a certain amount of benefit. Similar to a hiker's knapsack, the problem name suggests getting the most benefit for the specified amount of weight or space a knapsack can hold. Often, this type of problem allocates a budget, as the knapsack, and accepts as many projects as possible to maximize benefits. The general mathematical definition of the knapsack problem is:

Maximize

$$z = \{\mathbf{bx} | W\mathbf{x} \leq \mathbf{c}, x \in (0, 1)\}$$

where b_j = benefit from item j; W = weights of items; and c is the cost of the maximum size of items allowed, such as a budget. The decision variables, x_i, are at least integer but most likely binary, indicating that each item will either be included in the knapsack, $x_i = 1$, or left out of the knapsack, $x_i = 0$. The classic knapsack problem is characterized by the single constraint that often acts as a capacity constraint (maximization problem) or a lower bound on benefit (minimization problem).

The knapsack problem is a traditional method of exact algorithms to small scale portfolio optimization, or resource allocation, problems (22:14). There are many methods to solve this type of program; however, this research focuses on the formulation guidance from this problem, not its specific solution methods.

2.4.2 Direct Search Methods. When seeking to optimize a system, one must be aware of system characteristics, such as non-differentiability, that may limit the practical applications of common optimization tools. When designed experiments may be performed, but the function is not differentiable, direct search methods provide convergent optimal, to within a pre-set tolerance, solutions. Hooke and Jeeves first proposed this solution technique in 1961 defining it as a "sequential examination of trial solutions involving comparison of each trial solution with the 'best' obtained up to that time together with a strategy for determining what the next trial solution will be" (16:212). The distinguishing characteristics of direct search include the ability to address problems unsuccessfully solved

by classical methods, a reduced solution time for problems able to be solved by classical methods, an algorithm ideally applied on a computer, a continually improving solution set, and an ability to apply different assumptions. Simply described, direct search selects a base point and a second point, these are compared, the best selected, and a new basis is selected to obtain the next value for evaluation (26).

Why use direct search methods when more modern methods are now available? There are unique features of direct search that elude the problem of more sophisticated methods (21:2).

2.4.2.1 Pattern Search. *Pattern search* is a specific strategy for the direct search method that is characterized by its particular search strategy. There are many pattern search methods currently being used and researched. Most pattern search algorithms work on systems with continuous variables. Often when using pattern search for R&D designs, the variables are discrete. The pattern search strategy is accomplished by systematically evaluating local ranges of the variables and either accepting a new solution based on a better result, or rejecting the solution based on its inferior solution.

2.4.2.2 General Pattern Search Algorithm. The general algorithm for pattern search consists of the variables x_i, incremental step sizes ϵ for each x_i, and an assumption that past successful strategies will be successful in the future. It is this assumption that drives the two types of moves, *exploratory* moves and *search* moves. The procedure is as follows (14:113). Begin computation by selecting an initial, feasible exploratory point; the method by which this point is selected may provide a quicker solution, but any feasible point will do. Evaluate the objective function at this point X_1^*. Next evaluate $x_i \pm \epsilon$ to obtain the an objective value for $y(X_1^*)$. If there is improvement, that is, if $y(x_1 \pm \epsilon, x_2, x_3, ...x_n) > y(x_1, x_2, x_3, ...x_n)$ for a maximization problem, then this move was deemed a success and the $x_1 \pm \epsilon$ should be kept and the next x_i tried. Sequentially, all the independent variables are perturbed with respect to their shown improvement. The end of this sequence of moves establishes a *base point*, which is denoted X_1. Next, providing that the exploratory move produced some improvement, a pattern move is made to arrive at X_2^*. Once the exploration at this point produces X_2, an extrapolation of base points

X_1 and X_2 provides X_3^*. This process of "explore-and-extrapolate" is continued until no improvement is found. At that point, reduce all the ϵ by a constant factor and explore within a smaller region to obtain small improvements. If success is found, explore again, else reduce ϵ. The stopping criteria is a predefined minimal ϵ value (14:114-5).

Pattern search methods were initially used for continuous variables; however, this is often not the case in design projects, and discrete variables must be used. Booker *et. al.* discusses a helicopter blade design in (3:5).

2.4.3 Knapsack Search Heuristic. The multiple zero-one multiple knapsack heuristic proposed by Pirkul provides a satisfactory method for solving problems too large to be solved by optimal solution procedures. As the knapsack problem has been used to successfully model resource allocation, capital-budgeting, and other decision-making processes, so this procedure enables one to find a timely solution or at least a good base solution for an implicit enumeration method (29:161). Pirkul's problem involves the optimal solutions for problems with multiple knapsacks, but it is easily simplified to a problem with one resource constraint. Future efforts that combine multiple Army systems should take note of the multiple knapsack application. Noting successful use of "bang-for-buck" ratios, a ranked list aids in selecting variables to set equal one in the solution by simply evaluating the ratio of the objective function coefficient to the coefficient of the resource constraint, the benefit-cost ratio. The general approach selects the variables with the greatest b_i/c_i ratio, or the greatest likelihood of marginal benefit, to add to the objective function.

The formal heuristic procedure modified for a single portfolio is as follows. First, calculate the b_i/c_i ratios and sort all choices i in decreasing order. Next, fix variables equal to 1 based on order in the first step, and pay particular attention to not violating constraints. The base feasible solution is denoted $\bar{x}$. Finally, for each variable that is equal to 1 in $\bar{x}$, fix that variable to 1 and repeat the previous step to use the remainder of the resources and generate a new trial solution. For each base solution, there will be an associated number of trial solutions that equal the number of variables selected in the base solution. Following a single base solution, the best trial solution becomes the next base

point for a search. These iterative search regions continue until the predefined minimum improvement between variables has been reached (29:165).

This heuristic is very applicable to this study in that the traditional knapsack problem could not be implemented because of unavailable objective function coefficients. Direct search procedures for zero-one problems have not been clearly set nor proven to converge unlike the related direct search integer program (32). This heuristic allows for adjustment without violating assumptions of the method. It enables the calculation of acceptable answers to problems that the knapsack problem and the direct search procedure pose. In the future, development of a direct search procedure for zero-one problems will likely be published, and this technique should be first examined.

2.4.4 Optimization Summary. The technique for systematically examining portfolios integrates the output of the simulation model and the modified direct search techniques to recommend regions of acceptable response. Operationally, the Army addressed these issues using intuition and qualitative assessments. This methodology allows the decision maker to make qualitative assessments from the resulting quantitatively developed portfolios.

III. Methodology

3.1 Overview

This chapter discusses the methodology that was used to select the optimal set of controls to reduce the cost of accidents, the number of casualties, and the accident rate. The analysis can be divided into two sections: first, the Severity Reduction simulation which includes the Severity of Losses value model and second, the mathematical portfolio optimization program.

3.2 An explanation of the Severity Reduction Simulation.

The purpose of the severity reduction simulation is to produce the expected reduction in severity over 100,000 flight hours when a specific portfolio of controls is applied. One hundred thousand flight hours is the aviation standard measure for calculating accident rates. The percent difference between the expected severity for a portfolio with *no* controls applied and the portfolio with certain selected controls applied defines the reduction in severity. A single iteration of the simulation calculates the severity of the accidents selected for 100,000 flight hours as a specific portfolio is applied. The expected severity is obtained by completing multiple iterations, each calculating the severity for the given portfolio.

Monte Carlo simulation techniques are used to generate a number of possible accidents to select from the sample data to simulate a single 100,000 flight hour block. Reference to an *iteration* indicates a simulated set of accidents for five years worth of 100,000 flight hours blocks and the resulting severity, given the application of a specific portfolio of controls. The next sections describe necessary elements of the simulation in more detail.

3.2.1 ASIST Database. The Army Safety Center initiated the meeting of aviation industry and miliary experts to analyze accident data. This group of experts, the Aviation Safety Investment Strategy Team, ASIST, met to identify hazards causing individual accidents and address the possible controls that may be applied to reduce the likelihood or severity of the accident. Because the objective of the analysis was to take a

risk-based approach rather than a mistake-based or *blame-focused* look at accidents, the resulting information focuses on prevention (35:2000). Days of analysis by subject matter experts resulted in an extremely useful, focused set of accident cases. This foundational set of actual accidents included accident data, the hazards affecting these accidents, and the associated controls that reduce the effect of hazards. This database supports every part of the simulation.

3.2.1.1 Hazards. ASIST chose to set their focus on identifying hazards, not on identifying cause factors for specific accidents. A *hazard* is any factor contributing to the probability or severity of an accident. Defining hazards is significantly different from identifying causes. The distinction involves the focus of the analysis: hazards are *prevention* focused, while causes are *blame* focused. Analysis often emphasizes mistakes when identifying the causes; however, looking to hazards tends to create a concentration on risk. The taxonomy focuses attention on the parts of the man-machine-environment system which together produce hazards (13:50). The Army identified and published techniques for Risk Management most recently in Apr 1998, through FM 100-14. The hazards perspective provides the Army with methods of protecting of Army-wide investments (35:2000).

Building a hazard taxonomy to recognize risk involves viewing the accident cases with a new mindset, one that sees the mission, leadership, aircraft, and crew as contributors to the case as a whole. Combinations of all these parts may provide the most comprehensive determination of risk involved in the accidents as well as the degree to which soldiers are exposed to the risk (35:2000).

In addition to the development of the hazard taxonomy, ASIST assessed the hazard contribution for casualty, cost, and frequency. Each assessment estimates the percent a specific hazard contributes to the accident's cost, casualties, and occurrence. A hazard contributing to casualties specifically affects injuries and fatalities. A hazard's contribution to cost indicates the percent of the total accident cost for which this hazard was responsible. Finally, assessments of frequency refer to causes contributing to the occurrence of the accident. An example case with contributing hazards follows in Table 3.1.

Table 3.1 Contributing Hazards

Accident Case	Contributing Hazards	Casualties Contribution	Cost Contribution	Frequency Contribution
19931019001	OH58-58	50	50	50
	AVN-02	50	50	50
	Total	100	100	100
19960116001	AH64-62	0	1	8
	AH64-69	50	49	31
	AH64-70	0	1	15
	AH64-71	50	49	31
	AH64-85	0	0	15
	Total	100	100	100

3.2.1.2 Controls. As part of their analysis, ASIST identified controls which are actions taken to eliminate hazards or reduce their risk (8). A typical value model develops and evaluates alternatives based on what is important to the decision maker. For this study, controls are the alternatives; they were generated by the ASIST team in response to outstanding hazards. In ASIST, the controls were developed using the Army's Doctrine, Training, Leader Development, Organization, Material, and Soldier Performance (DTLOMS) framework. Controls may affect more than one hazard, each with a different effectiveness. MIL-STD-882 system safety design order of preference determines the individual control effectiveness estimates:

Table 3.2 Control Effectiveness Estimates

1.	Design for minimum risk	80-100%
2.	Safety devices	60-80%
3.	Warning devices	40-60%
4.	Procedures and training	20-40

The individual control effectiveness estimates for each hazard indicate the assessed percent reduction. The area experts, Army aviators and other members of ASIST, dedicated many long hours to estimating hazard reduction achieved at the end of ten years of control application. ASIST has proposed, to date, 353 controls for the force-modernized aircraft addressed in this study.

Control cost is categorized by the range of possible expenditures for 20-year implementation fleetwide. The optimization uses the median value of the probable range to estimate cost. Because controls will be selected for fleetwide use, individual aircraft cost is not considered. Although only estimates, these costs provide a resource value by which controls may be added to budget-specific portfolios.

Table 3.3 Estimated Control Cost Ranges

20 year fleetwide cost		Point Est. Cost
\$ 0 - 100K	nil	\$ 50,000
\$ 100K - 1M	very low	\$ 500,000
\$ 1M - 38M	low	\$ 19,000,000
\$ 38M - 150M	medium	\$ 90,000,000
> \$ 150M	high	\$ 200,000,000

3.2.2 Possible Accident Input. In the simulation, the possible accidents for each iteration are randomly drawn from past accident reports. Replacement of the accident data allows the possibility of the same accident occurring more than once within a single iteration. Due to the aggregation of all accident data for the force modernized aircraft, AH-64, CH/MH-47, UH/MH-60, and OH-58D, the number of possible accidents for each iteration is based on their overall accident rate during the past seven years. This method of accident selection permits the future accidents per aircraft type to be based on the accident data. This removes the need to aggregate by aircraft type using normalized hours flown or hours per actual aircraft per month.

By inspecting the accident cases, it is noted that accidents occur independently of one another. The number of possible incidents in an interval of 100,000 flight hours can be represented by a Poisson random variate (20:390). Each case represents a single incident occurring at one point in time, which meets the first property of a Poisson process. Next, the occurrence of accidents in one 100,000 flight-hour unit is not dependent on previous incidents or on "run-up" time, as with the stand-up of a system. The occurrence of accidents in one set of 100,000 flight hours is independent from accidents occurring in a completely separate or even an overlapping set of 100,000 flight hours. Thus, a Poisson random variate is well suited for generating inputs in this simulation.

The most recent accident occurrence information best forecasts future accident occurrences. Future possible accidents are derived from the Poisson distributed accident rates for FY94 to FY00, the period ASIST has analyzed to the present. The actual number of possible accidents in one iteration is produced by a random variate generator based on the Poisson distributed accident data; for this analysis, a Poisson distribution with parameter $\lambda = 11.89$, the mean estimated from the accident data available.

3.2.3 Control Effectiveness. Each selected control reduces the occurrence or likelihood of certain hazards by an appropriate efficiency designated by the ASIST team. The controls do not reduce all hazards with the same efficiency. For this reason, the lists of controls must be examined to ensure that every hazard reduced by the selected portfolio of controls is included. If multiple controls help reduce the same hazard, the difference in reduction amounts must be addressed. When ASIST decided these effectiveness measures, they called it a reduction in the *likelihood* of an accident. It is assumed in the study that each reduction is to be taken from the remaining likelihood of an accident. Consider this situation: three different controls all reduce the same hazard, but by different amounts. If control H47-C05 reduces hazard H47-12 by 0.5; control H47-C16, by 0.5; and control H47-C45, by 0.25, we cannot say that the total reduction for H47-12 is 1.25. Noting the difficulty in completely evaluating the hazard list resulting from every control combination, a generic method of combining reductions is suggested. The additive, but not greater than 1.0 model may simplify calculations, but such an approach incorrectly assumes that hazards may be completely eliminated. A more conservative, and more realistic method of integrating the hazards is a multiplicative combination, where e_i represents the individual effectiveness values:

$$Combined\_Hazard\_Reduction = 1 - \prod_{1}^{i}(1 - e_i).$$

Therefore take 25% of 50% of 50%; the result is a reduction of 0.8125. This is the hazard reduction input into the model.

3.2.4 Severity of Losses Model. The Army Safety Center seeks to reduce accident severity by 50% over the next ten years (beginning April 1999). By reducing accident severity, the important underlying issues, casualties and total cost, are also reduced. The Severity of Losses model is a value-focused thinking model which addresses the important facets of accident severity and accounts for the preferences of commanders to describe why severity is important. For the purpose of this analysis, it is assumed that reducing the frequency or severity of contributing hazards should reduce the overall losses associated with the accidents. The model describes the severity of accidents in 100,000 flight hours. Severity, from a safety standpoint, must be minimized. To support a model that experts and users alike understand, a value of 1.0 is given to the worst severity score, and a severity score of 0.0 is the best, or least severe. Value-focused thinking models often scale all alternatives on a 0 to 1 scale; however for severity, the goal is to obtain a score near zero (19).

Army FM 100-14, entitled "Risk Management," states four criteria for assessing severity: degree of injury or illness, repair or replacement costs, other mission impairing factors, and environmental damage (8:2-9). From these criteria, the top tier of the hierarchy is derived: *casualties* corresponds to the degree of injury or illness, *unit readiness* corresponds to other mission-impairing factors, *total costs* correspond to loss of or damage to equipment or property, and *environmental damage* remains.

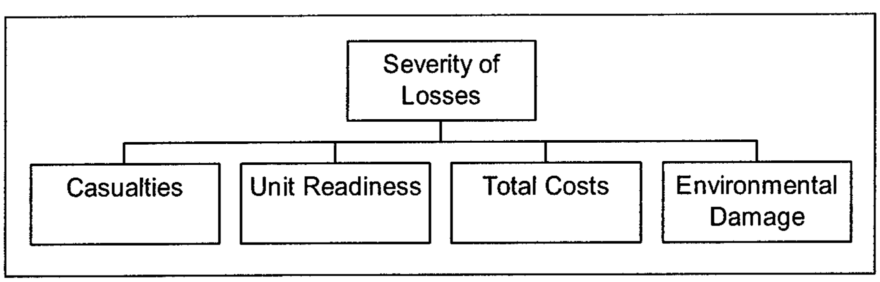

Figure 3.1 Top Level of Severity of Losses Hierarchy

Each of these objectives are supported in FM 100-14 as the key objectives describing severity. The following sections address the reasons behind the development of these

branches. The severity functions for every evaluation measure are completely developed in detail in Appendix A.

3.2.4.1 Casualties. *Casualties* measures the contribution to severity made by fatalities and injuries sustained due to accidents. According to Army Risk Management, FM 100-14, and USASC leadership, the following subobjectives effectively measure *casualties* contribution to severity from the Army-level perspective (Warren, 2000). These components are shown in Figure 3.2 and addressed individually in the following subsections.

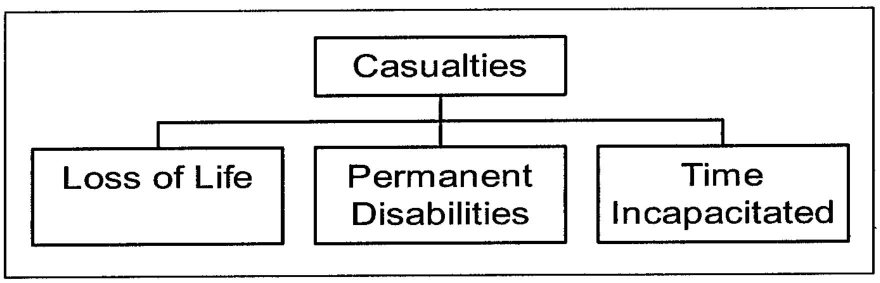

Figure 3.2 Sub-objectives for Casualties

Loss of Life assesses the impact of all fatalities on the Army; it measures the severity of the number of fatalities for 100,000 flight hours. This natural-direct measure includes all fatalities resulting from an accident, military and civilian personnel.

Permanent disabilities fall into two categories, partial and total. The Army Safety center tracks both types of injuries in the Risk Management Information Database (RMIS). *Total disabilities,* as determined by the opinion of competent medical authority, compromise any nonfatal injury that permanently and totally incapacitates a person to the extent that he or she cannot find any gainful employment (DA PAM 385-40, 1994: Glossary). Rarely do these types of injuries result from aviation accidents. The Severity of Losses model accounts for this type of loss; however, due to the lack of any occurrence of permanent total disabilities in this data sample, this measure is not used in this study.

Permanent partial disabilities is a natural-direct measure, and it assesses the contribution to severity of losses from permanent disabilities. Although also rare, its occurrence is severe enough to include in the model. A permanent partial disability is any injury (not

resulting in death or permanent total disability) that, in the opinion of competent medical authority, results in the loss or permanent impairment of any part of the body, with the following exceptions:

1. Loss of teeth.
2. Loss of fingernails or toenails.
3. Loss of tip of fingers or tip of toe without bone involvement.
4. Inguinal hernia, if it is repaired.
5. Disfigurement
6. Sprains that do not cause permanent limitation of motion

(DA PAM 385-40, Glossary).

Time incapacitated is a natural-direct measure of the severity of losses resulting from days of hospitalization due to aviation accidents. "Admission to a hospital as an inpatient for medical treatment" officially defines hospitialization (DA PAM 385-40, 1994: Glossary). Days hospitalized counts only the hospitalization of military personnel.

3.2.4.2 Unit Readiness. Any loss not only affects the Army as a whole, it certainly directly impacts the individual units as well. The *unit readiness* objective measures the severity of losses in terms of the impact these losses have on individual battalions. As representative of FM 100-14's mission-impairing factors, unit readiness identifies the following sub-objectives as major contributing factors: *training execution*, *unit morale*, and *equipment availability.*

Training execution is a natural-proxy scale that assesses the impact of decreased training on unit readiness. Commanders are believed to become more risk averse as accidents increase within the unit. The battalion commander may react to recent accidents by reducing the complexity, realism, sophistication of training, or amount of training for the unit. This change in mission plans and execution results in decreased unit readiness. *Training execution* measures the number and class of the accidents that occur in a single unit. Assessment and opinions here are drawn from an interview with LTC Semmens (13).

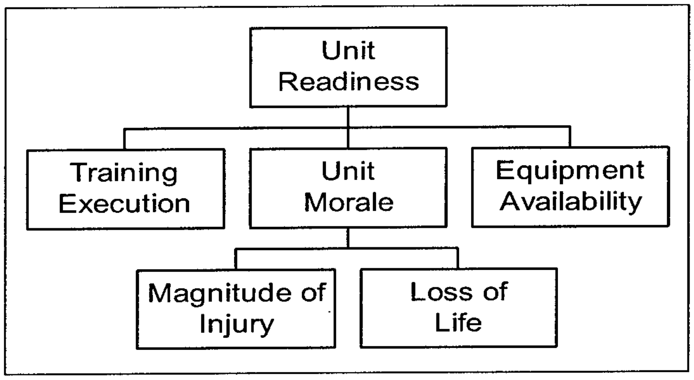

Figure 3.3 Sub-objectives for Unit Readiness

Soldiers within a unit drive the level of readiness. Any decrease in *unit morale* will have a detrimental effect on unit readiness. Although many issues may be identified to assess the impact of aircraft accidents on unit morale, two major influences were identified: *loss of life* and *magnitude of injury*. *Loss of life* is a natural-proxy measure for assessing the decrease in unit morale due to the number of fatalities in the unit. The emotional impact on soldiers affects performance and consequently unit morale. Acknowledging that fatalities are not the only factor impacting unit morale, *magnitude of injury* uses a constructed scale to measure how permanent disabilities and hospitalizations of fellow soldiers result in decreased morale. This proxy scale is weighted to indicate that permanent injuries have a large impact, as do lengthy hospitalizations.

Table 3.4 Injury Category Classification

Category 0:	No injuries requiring hospitalization
Category 1:	Injuries requiring ≤ 7 days hospitalization
Category 2:	Injuries requiring > 7 days hospitalization, no permanent disabilities
Category 3:	Injuries resulting in permanent disabilities

Equipment availability assesses the impact on unit readiness of having fewer aircraft for a unit. This natural-proxy measure assesses the number of unavailable aircraft within the unit. An aircraft is defined *unavailable* when it is deemed a total loss or requires greater than 40 man-hours to repair. If an aircraft requires more than 40 man-hours to repair, it is assumed that repairs would not be accomplished at the unit level, but rather at post or depot level (13). An aircraft will be considered a *total loss* when it is not

economically repairable. An estimate of man-hours required first appears in the accident report; however, the final number of hours necessary are recorded and this study uses this man-hour total. Time to assess and estimate damage, as well as repair and replace damaged and not economically repairable parts, are all counted for the final total (9:2-11).

3.2.4.3 Total Costs. *Total costs* is a natural-direct measure assessing the severity of accidents in terms of the dollar cost to the Army. Army Regulation 735-11 includes the following as Army accident costs: injury costs, repair/replacement costs, and other military and non-military damage costs resulting from accidents. Accident investigation teams use accident cost to determine the classification.

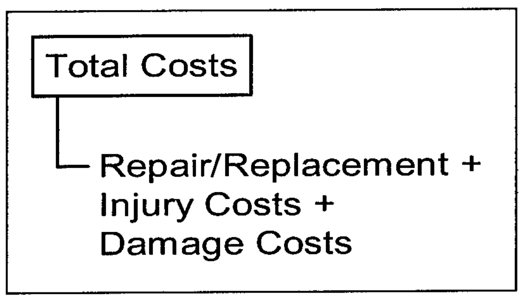

Figure 3.4 Details of Total Cost Objective

Repair and replacement costs include all costs incurred from aircraft damage. In the event of a total loss, the acquisition cost is used as the cost to replace. If the aircraft is repairable, man-hour costs and parts replacement costs will be used (9:2-11).

Injury costs include medical expenses; however, they do not estimate the monetary loss incurred while the soldier is not mission capable. Specifically, indirect costs associated with the accident such as production loss, or wages lost to employees not injured, and the cost of hiring and training new employees are not included. Injury costs consist of the cost of pay while away from work, medical treatment, hospitalization, dependent survival, unused training costs, gratuities, compensation, disability retirement, and burial. An actual time away from work is included, if known, when the accident report is submitted; otherwise, an estimate of lost workdays made by a competent medical authority is used (9:2-11).

3.2.4.4 Environmental Damage. The final objective contributing to the severity of losses is *environmental damage.* Balancing damage to the environment against national objectives, often means choosing the national objective, yet doing everything reasonable to minimize environmental damage. The US Army Engineer School, the executive agent for Military Environmental Protection, provides the applicable sub-objectives in the Military Environmental Protection Manual (7). Damage is categorized by the element damaged; the Army is concerned with spills that will damage the soil and water. Aircraft accidents may leak fuel, hydraulic fluid and oil. Currently, a detailed assessment of environmental damage is not available due to the lack of data.

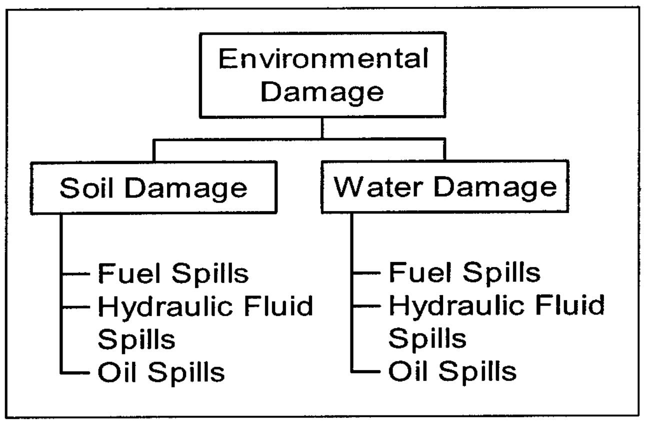

Figure 3.5 Sub-objectives for Environmental Damage

The Army categorizes hazardous fluid spills by the number of gallons spilled. Because of its importance, the measures for an assessment of severity based on spill type and environment rely on this limited information. The constructed-direct measure of severity of environmental damage accounts for effects on environment and clean-up required.

Table 3.5 Hazardous Fluid Spills Classification

Category 0:	No hazardous fluid spilled
Category 1:	Less than 1 gallon of hazardous fluid spilled
Category 2:	More than 1 gallon, but less than 2 gallons
Category 3:	More than 2 gallons, but less than 10 gallons
Category 4:	More than 10 gallons, but less than 20 gallons
Category 5:	More than 20 gallons spilled

3.2.5 Bootstrapping Using Monte-Carlo Simulation. Bootstrapping statistics using Monte-Carlo samples is employed in this simulation by using Palisade's @RISK software. This technique statistically samples and analyzes data from an unknown distribution. The number of possible accidents for one iteration is generated by a pre-defined random Poisson variate. Once the number of accidents to evaluate has been selected, the actual accidents to be simulated are drawn randomly, with replacement, from the complete list of cases evaluated by ASIST. Independence of runs is assumed.

3.2.5.1 Number of Sample Runs. The number of runs in part determines the accuracy of an estimator. The estimator of interest for this study is *percent severity reduction*, as generated by the Severity Reduction Simulation. To evaluate portfolios of controls with regard to one another, an estimate of the performance measure within an accuracy ϵ with specified confidence $100(1-\alpha)\%$ must be known. To determine the number of runs necessary to obtain the relevant statistics, means and 90% confidence intervals, use of the equation for the student t statistic allows for the determination of the number of replications, R, needed. R replications are always greater than R_o sample runs (2:439).

$R \geq (t_{\alpha/2,\text{R-1}} \times S_o/\epsilon)^2$ where $\alpha = 0.1$, S_o^2 = the variance for R_o sample runs, and $t_{\alpha/2,\text{R-1}}$ is determined from the student t tables. For this study, the average severity reduction for 27 blocks of 100,000 flight hours, an estimated five year period, composes a single sample run. The variance observed for a particular run is $S_o = 0.00033$. The specified accuracy is $\epsilon = 0.01$, or 1%.

Using the cumulative normal distribution,

$$R \geq (z_{\alpha/2} \times S_o/\epsilon)^2 = (1.645^2 \times 0.00033/0.01^2) = 8.93.$$

Since R must be ≥ 9, proceeding with the student$-t$ equations, the smallest integer R that satisfies the inequality is 11: $11 \geq (1.81^2 \times 0.00033/0.01^2) = 10.81$.

Thus, to estimate the mean, 11 replications must be performed. In accordance with Efron and Tibshirani, ten times the number of replications should be performed to accurately estimate the confidence intervals using the bootstrap method. Therefore,

110 replications are run when estimating confidence intervals. The expected Severity Reduction for any one block of 100,000 flight hours in the estimated five years of Army flight hours is passed to the optimization program.

3.2.6 Process Overview. One iteration consists of a portfolio of controls input, a possible accident draw, and a severity reduction output. First, because each control has a reduction efficiency for certain hazards, the input control list is reviewed and translated into terms of hazards and their effectiveness. Next, the assigned number of accidents from the draw are selected from the database and, where applicable, the accident data is reduced as it could have happened when the control was applied. The resulting cumulative accident data for one iteration is next evaluated in the Severity of Losses value model to obtain the Severity value for both what the accidents would have been without the portfolio of controls and what the accidents result is with the portfolio applied. As previously mentioned, this procedure is repeated to obtain reliable statistics for its expected value. A detailed explanation is included in Appendix B.

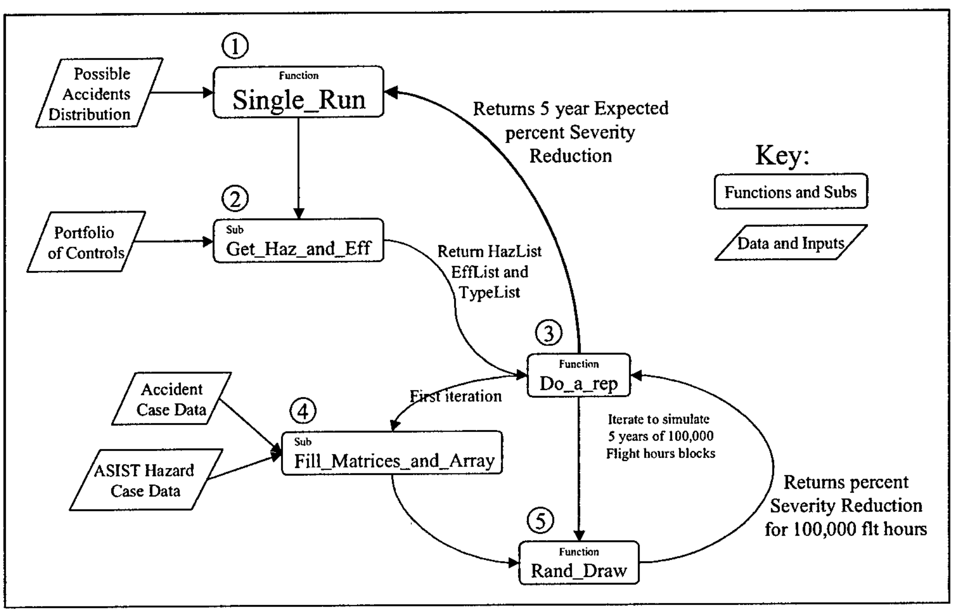

Figure 3.6 The Severity Reduction Simulation Complete Process Diagram

3.3 Optimizing the Portfolios

The Army's objective is to obtain a 50% reduction in accident severity, to gain the greatest reduction in accident rate, accident cost, and casualties. The first section of this chapter established the model which returns an accepted estimate of severity reduction, an overall measure of the Army's objective. This section establishes the best technique for selecting sets of controls based on a given budget. This study analyzes a set of 353 controls. Each control may be selected, or may not be selected for the portfolio; this results in 2^{353}, or 1.8×10^{106} different possible portfolios, clearly computationally intractable to completely enumerate.

3.3.1 Unique Problem Characteristics. This portfolio selection problem is unique because of several features: first, the objective function is not differentiable; second, the interaction between controls is unpredictable; and third, the size of the problem makes enumeration impossible. There are procedures in existence to accommodate some of these characteristics, and an eclectic approach that ensures key assumptions are met is the best solution.

It is possible to evaluate controls individually and then take a traditional portfolio optimization approach as suggested by Kirkwood or Keeney; however, both assume additivity of the values (19:207). The nature of the ASIST data set, as described in Section 3.2.3, and the case information suggest that an additive severity reduction is not appropriate. Consequently, the fundamental assumption based on the data sets is that when multiple controls are applied, a synergistic effect may be observed. By observing the expected severity reduction of a specified portfolio, iterative adjustments provide insight into the possible interactions present returning the greatest improvement.

3.3.2 The Search Procedure. Following Pirkul's multiple knapsack heuristic, pertinent observations may be made and useful solutions can be obtained. The Severity Reduction Simulation takes a portfolio and accident distribution input and returns the expected severity reduction (%) for that portfolio. In order to estimate the impact each control makes when it is evaluated alone, a portfolio is created with only one control in it.

Obtaining a reasonable starting point begins by evaluating all 353 single control portfolios. Acknowledging that the sum of these reductions by themselves exceed 1.0, the interactions must be both positive and negative. In addition, there are specific constraints inherent to the controls that must be considered. For example H47-C09 and H47-C10 would never logically be applied simultaneously. To avoid this procedure recommending infeasible portfolios, multiple choice constraints, as appropriate, are built into the base portfolio optimization procedure.

The program developed in the study uses traditional binary integer programming techniques to maximize a surrogate objective function where the coefficients for each decision variable are the reduction values from the each single control portfolio. The constraints consist of the resource constraint, the budget, and the mutually exclusive control application constraints that restrict specific combinations. Finally as defined by the program type, all decision variables in this program are binary. The solution obtained by this surrogate objective function purely estimates the magnitude of reduction. The actual percent severity reduction returned by the specified portfolio is less than the surrogate.

Base points for several levels of representative budgets are analyzed; the results provide insights into what the expected level of reduction for a given budget could be. In each additional portfolio analysis, the knapsack's resource constraint, in this case budget, appears. A linear comparison of what the integer program expects versus what the Severity Reduction Simulation actually returns initially reveals the direction that the expansion should take.

Incorporating direct search derivative-free methodology, effective and efficient use of the severity reduction simulation can be observed. The knapsack heuristic generates a set of local portfolios out of modified base portfolios, and seeking to identify improvement in those base portfolios. This iterative replacement of variables with those having a high benefit-cost ratio enables new interactions to appear while feasibility is maintained. This effective method of identifying local improvement may help identify portfolios that contain synergistic interactions.

					Test Portfolios										
Control	**Severity Reduction**	**Cost ($M)**	**Benefit/Cost Ratio**	**Base Portfolio**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	
AH64-C28	0.000001	0.05	0.000015	1	0	1	1	1	1	1	1	1	1	1	
AH64-C38	0.014863	0.50	0.029726	1	1	0	1	1	1	1	1	1	1	1	
AH64-C56	0.026011	19.00	0.001369	1	1	1	0	1	1	1	1	1	1	1	
AH64-C86	0.000036	90.00	0.000000	0	0	0	0	0	1	0	0	0	0	0	*1
H47-C06	0.007159	19.00	0.000377	1	1	1	1	0	1	1	1	1	1	1	
H47-C100	0.009747	200.00	0.000049	1	1	1	1	1	0	1	1	1	1	1	
H47-C65	0.000091	0.05	0.001813	1	1	1	1	1	1	0	1	1	1	1	
H47-C96	0.000725	0.05	0.014490	1	1	1	1	1	1	1	0	1	1	1	
H60-C09	0.034728	19.00	0.001828	1	1	1	1	1	1	1	1	0	1	1	
H60-C34	0.035315	200.00	0.000177	0	0	0	0	0	0	0	0	0	0	0	*2
H60-C41	0.030657	0.05	0.613133	0	0	1	1	1	1	0	0	1	1	1	
H60-C44	0.029879	90.00	0.000332	0	0	0	0	0	1	0	0	0	0	0	
OH58-C03	0.012381	90.00	0.000138	1	1	1	1	1	1	1	1	1	0	1	
OH58-C11	0.003072	0.05	0.061440	0	0	1	1	1	1	0	0	1	1	1	
OH58-C31	0.009477	19.00	0.000499	1	1	1	1	1	1	1	1	1	1	0	
OH58-C72	0.000058	0.05	0.001154	0	0	1	1	1	1	0	0	1	1	1	*3

Figure 3.7 Example of Knapsack Heuristic Generation of Test Portfolios

3.3.2.1 A Knapsack Heuristic Example. This example uses actual controls, their individual severity reductions, and estimated cost. As displayed in Figure 3.7, the number of selected items in the initial base portfolio indicates the number of test portfolios generated for the local region. A new test portfolio is generated by setting each 1 equal to 0 and placing the remaining budget slack into other unselected controls to fill the budget keeping the portfolio feasible. There are four possible trends for the unselected controls to assume in the test portfolios generated by the method. First (indicated by *1 in the table from Figure 3.7) a control may be selected infrequently, such as the case when an expensive control is unselected. A second possible trend is seen in note *2 (in the table from Figure 3.7); this control is never selected often due to high cost and low reduction. The third, and most common trend, occurs when a control is selected because of a high benefit-cost ratio, but this is dependent on available slack budget (see note *3 in the table from Figure 3.7). The final, and not displayed, trend is the always selected control. Unselected variables in the lowest cost category with high benefit-cost can be selected with priority for each additional test portfolio. Each selected variable, as indicated by a 1 in the *test portfolio* column, initiates the formation of test portfolios. The values returned for each

test portfolio may show improvement; estimates about the mean, standard deviation and confidence intervals indicate any statistical difference in the portfolios.

3.4 Methodology Summary

This methodology enables the Safety Center to incorporate ASIST analysis and Risk Management Information System (RMIS) data into a samples that demonstrate accident sets based on an accepted standard of severity. The Severity of Losses model defines the factors of severity that are most important for a balanced evaluation of severity. The Severity Reduction simulation evaluates each portfolio of controls and is able to provide the 90% confidence interval for the expected mean Severity Reduction. Using Direct Search techniques to make the best use of the simulation results, the objective values returned by the simulation are evaluated using a multiple choice knapsack heuristic. The following chapter explores the results of this methodology applied to the control-portfolio selection problem.

IV. Severity Reduction Analysis

4.1 Top-Level Portfolio Selection Overview

This research develops a tool that enables the Army Safety Center to select a portfolio of controls that reduces severity of aviation accidents by 50%; as an example, use the force modernized aircraft, AH-64, CH/MH-47, OH-58D, and UH/MH-60. This goal, set by the Under Secretary for Acquisition and Technology, Army, involves incorporating the risk management process with available accident investigation information and ASIST-identified hazards and controls. ASIST first performed a hazard analysis that both identified hazards and the accident cases involving them. Next, ASIST looked at each accident case and the hazards contributing to it and assigned what percent of the total cost, casualties, and frequency of the accident each hazard was responsible for. These percent contribution values quantify the preventative components of each accident. The controls generated by ASIST are tailored to fit individual hazards and eliminate their influence on the fleet. ASIST hypothesized effectiveness values for every control-hazard pair; these unique pair combinations allow controls to impact multiple hazards with different values. Meeting the Army goal requires examining selected sets of controls, *portfolios of controls*, and finding the combination that returns the greatest reduction in accidents for a given budget amount.

Selecting an individual control or obtaining a ranked list of top controls requires an understanding of what makes a control effective. Speaking outside of the Severity Reduction Simulation for a moment, if a specific type of accident occurred frequently, for example a tree strike, the following actual hazard statement would capture the occurrence of such an event:

Table 4.1 Example Hazard Statement

Hazard H60-06	Loss of situational awareness (as a result of distance estimation, varying workload, environmental, and visual issues) while maneuvering in close proximity to trees or objects may result in the aircraft striking the trees or objects.

Several controls proposed by ASIST aid the elimination of this hazard. The Safety Center generally assumes that a hazard will not be entirely eliminated; however, it is possible to nearly eliminate some types of hazards by implementing tractable controls. Specific controls that impact hazard H60-06 are listed in Table 4.2.

Table 4.2 Controls that Impact Hazard H60-06

Control	Control Statement	Effectiveness
H60-C03	Change ATM to establish new flying hour category for individual task flight training hours and resource individual training.	0.25
H60-C06	Establish and sustain crewchief's "school house" training program	0.35
H60-C07	Establish crew coordination sustainment program	0.5
H60-C08	Establish standards for and resource a 4th crew member for high workload ops	0.45
H60-C10	Implement a change to the flight control system to improve aircraft stability and control in low speed flight (Attitude Command Attitude Hold)	0.5
H60-C11	Increase the available aircrew experience	0.25
H60-C16	Develop and field a proximity warning system (Virtual Rotor Disk)	0.7
H60-C24	Develop and install new Night Vision Systems	0.5

This table indicates the numerous possible 'solutions' to the hazard problem stated above. Each hazard within the system has at least one control that may be selected to reduce its likelihood or severity. Generally, the more controls selected to reduce a single hazard, the less frequently it will occur. The conscious selection of controls involves analyzing accident cases to identify the most frequent and most severe hazards, observing the controls that act to reduce these particular hazards, and simulating the interactions of simultaneously applied controls.

This chapter addresses the percent severity reduction output obtained by simulated portfolios and identifies valuable insights from the reductions gained by these. The search procedure first explores the output obtained from an integer programming solution, then it

investigates the local region. The goal was to obtain a single optimal portfolio of controls; however, this analysis displays the actual plethora of reasonable control portfolios with an explanation of the response and the justification for future recommendations.

4.2 The Integer Problem

This problem takes input from the Severity Reduction Simulation and focuses on returning a good starting solution. The analysis begins with the single control portfolios, then the formulation of the problem, and finally insights gained by this process.

4.2.1 Individual Control Effectiveness. Implementing single control portfolios allowed each control to be evaluated to determine its mean percent severity reduction for blocks of 100,000 flight hours over five years in the force modernized aircraft addressed. Controls are designed to reduce accidents for a particular airframe; hazards may affect multiple airframes. The percent composition, by airframe, of the ASIST-evaluated accident cases, FY94 through FY98, reveals the possible accident draw likelihood as depicted in Figure 4.1. Estimation of the severity contribution of each airframe requires a common factor, such as percent of total hours flown by a specific airframe, to combine severity scores. It may be estimated, that the percent of actual incidents in each airframe is a better standard by which to aggregate severity than the percent total hours flown in a year. From the information contained in this chart, the cumulative distribution representing the percentiles explains the selection of possible accidents.

An individual control's severity reduction must be less than the affected aircraft's percent composition of the data set because if it was possible to decrease all accidents for that type, the overall severity reduction is expected to be same as percent composition. A specific hazard may cause several incidents within a selected set of data, the simple relative volume of accidents caused by a particular hazard can indicate its severity. By selecting a control that reduces these most commonly occurring hazards, the overall severity is decreased. When an individual control is applied, it reduces the accident severity for that type of airframe. The best reduction found by this study for any single control portfolio

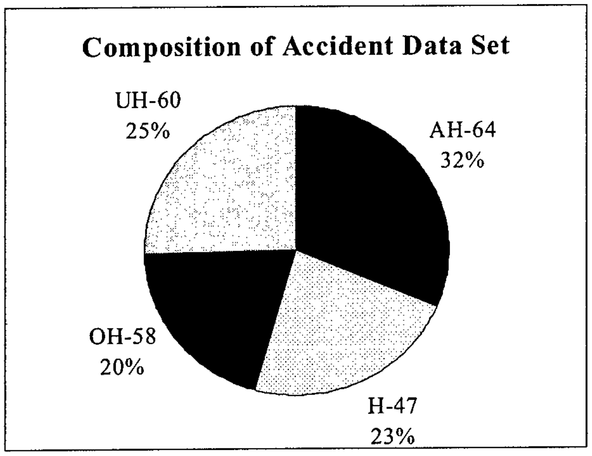

Figure 4.1 Cumulative Composition of the Data Set by Airframe

is less than 4% over all the force modernized aircraft. The single control reductions serve to estimate the possible multiple control portfolios.

4.2.2 Problem Formulation. This problem solves the surrogate objective function for an estimated Severity Reduction value. These surrogate function coefficients were derived by finding the mean reduction when a portfolio consisted of a single control. The budget serves as the primary knapsack resource constraint. The additional constraints in this integer program serve to eliminate the application of overlapping controls. Insights into the process has led the Safety Center to remove a few decision variables from the set, these variables will always equal zero. There are 353 variables and 15 constraints. The X_i variables are the binary control selection variables, the R_i variables are the reduction values, and the C_i variables are the cost of individual controls. The objective is to estimate the largest percent reduction obtainable from the combination of controls. The model is:

$$\text{Maximize} Z = \sum R_i \cdot X_i \qquad \text{(SLP)}$$

subject to

$$\begin{aligned}
C_i \cdot X_i &\leq Budget \\
AH64C22 + AH64C26 &\leq 1 \\
AH64C52 + AH64C53 &\leq 1 \\
H47C87 + H47C124 &\leq 1 \\
H47C105 + H47C127 &\leq 1 \\
H47C52 + H47C127 &\leq 1 \\
H47C103 + H47C127 &\leq 1 \\
H47C09 + H47C10 &\leq 1 \\
H60C34 - H60C44 &\leq 0 \\
H60C25 + H60C46 &\leq 1 \\
H60C16 + H60C20 &\leq 1 \\
H60C20 + H60C21 &\leq 1 \\
H60C15 + H60C24 &\leq 1 \\
H60C17 + H60C44 &\leq 1 \\
3AH64C65 - AH64C66 - AH64C67 - AH64C69 &\leq 0 \\
X_i = \{0, 1\}
\end{aligned}$$

Solving this surrogate linear program returns an appropriate, reasonable starting portfolio given a budget. Discussion with the Army Safety Center led to the establishment of a $1 billion budget. Sensitivity analysis about this fixed budget has been performed for a wide range of cost ($M) because the controls selected to be funded by the Army are not based on filling a given budget, but meeting the set reduction goals. Therefore, acceptance of a budgeted portfolio of controls depends on the quality of the contents of the items in the Program Objective Memorandum (POM). The Safety Center budget allocations for the application of controls are based not on overall cost, but rather on likely outcome received.

The linear program assumes an additive objective function. Using Frontline System's Premium Solver Platform, to find the solution to the linear program given by SLP, the optimal base portfolio is found. It can be seen through testing (see Figure 4.2) that the sum

of single control portfolios is not necessarily equal to the severity reduction value obtained from the portfolio containing the same controls. Therefore, the value of the surrogate objective function is an ordinal representation of the magnitude of severity reduction, not an actual expected percent severity reduction.

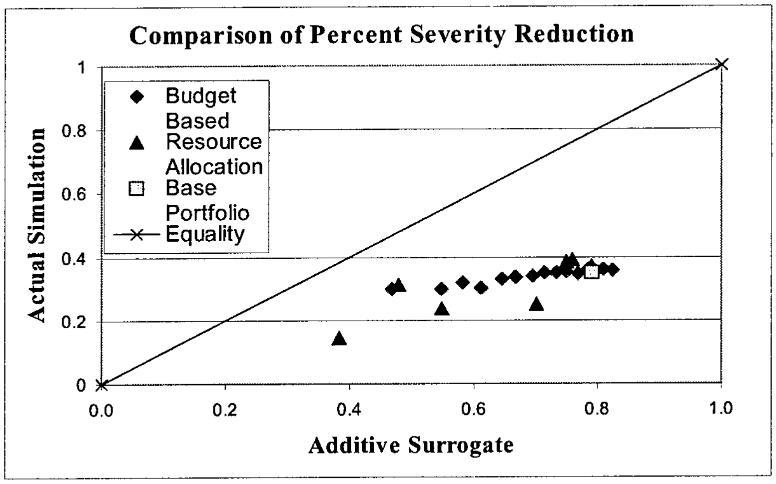

Figure 4.2 Demonstration of Inadequacies of Surrogate Objective Value Compared to the Simulated Value

From Figure 4.2 the base portfolio (□) consists of 159 controls selected to maximize percent severity reduction. This portfolio returns an expected severity reduction of 35 percent. For comparison, several potential starting portfolios (▲) were derived using various resource allocation techniques, including a cost-effectiveness ratio, best individual severity reduction, and largest number of controls method. Another comparison standard used the integer program with surrogate objective function to generate different portfolios (♦) by varying the budget constraint. The following chart identifies the predicted surrogate reduction in severity (x-axis) versus the actual observed mean reduction in severity (y-axis). These clearly sub-optimal methods of completing the base portfolio indicate that, although the surrogate function is known to be nebulous in its definition, it is an ordinal representative of the actual percent severity reduction values.

4.3 Optimal Region Search

The base portfolio resulted from fixing the budget to one billion dollars in the resource constraint. Given this initial solution, this study examines the improvement gained by interchanging particular controls and searching in the local regions. The method for searching the region near the base portfolio removes each selected control individually and utilizes the allocated budget to purchase the unselected control(s) that have the highest cost-effectiveness.

The knapsack heuristic modified as described in Chapter Three utilizes this base portfolio to generate 159 new test portfolios to examine for improvement. The results of this test indicate extremely small variation in the value range; no statistically different portfolios resulted from this first examination. Figure 4.3 indicates the surrogate objective value plotted versus the actual percent severity reduction observed by the simulation. This portfolio solution displays a high degree of degeneracy arising from minute differences in individual control reductions. The maximum surrogate value frontier appears at 0.75 because the surrogate optimal function was found and multiple test portfolios with minimal surrogate value differences exist near this value.

Sensitivity analysis to budget levels was then examined. In an investigation of portfolios at $750 million and $1.5 billion, very similar output occurred about the local regions, see Figure 4.4. Although the surrogate objective function increased, the actual severity value observed by the simulation indicated little increase for the $750 million budget increase. These regions also displayed a highly degenerate base portfolio.

The level of degeneracy led to a closer inspection of control cost and how its increase affects the portfolio selection. For example, if all of the controls costing over $19 million are eliminated from consideration, the resulting portfolio generated from this constrained problem reveals selection preference. The order of magnitude differences between cost make selection of high budget controls, those over $20 million, very rare.

Examination of high-performing controls also provide insight into the types of controls returning maximum effectiveness. The cost-reduction comparison table that follows identifies any effectiveness trends related to cost. These mean and observed reductions

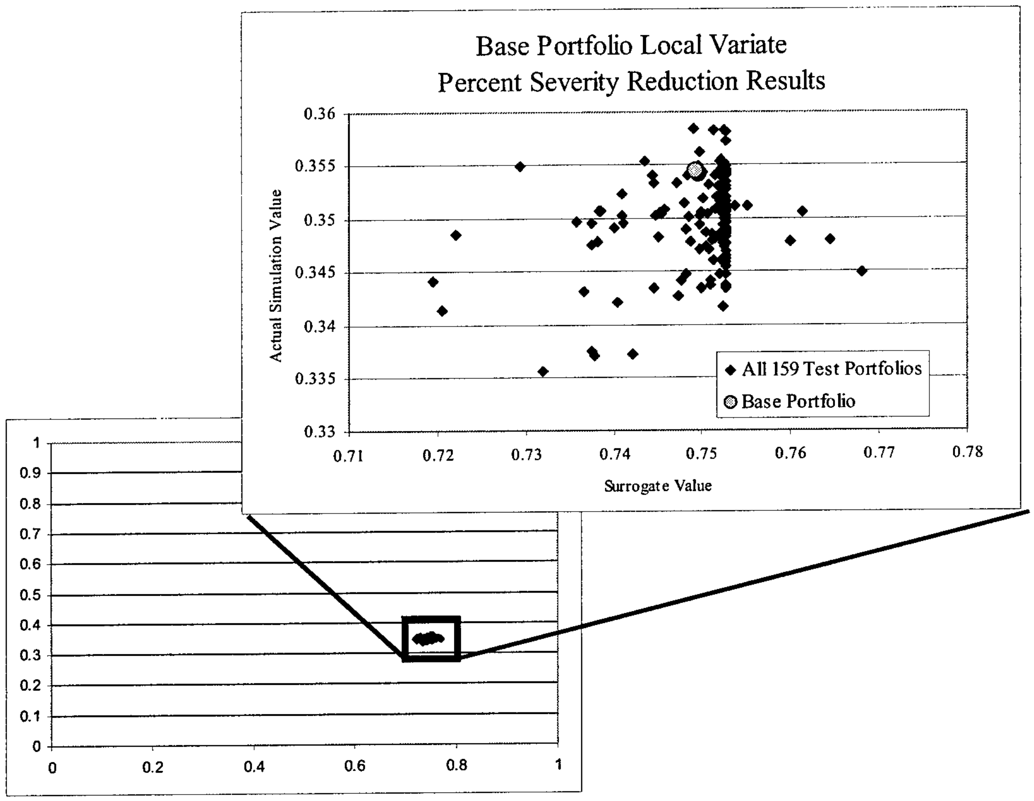

Figure 4.3 Base Portfolio Exploration of Local Region, a Complete Perspective

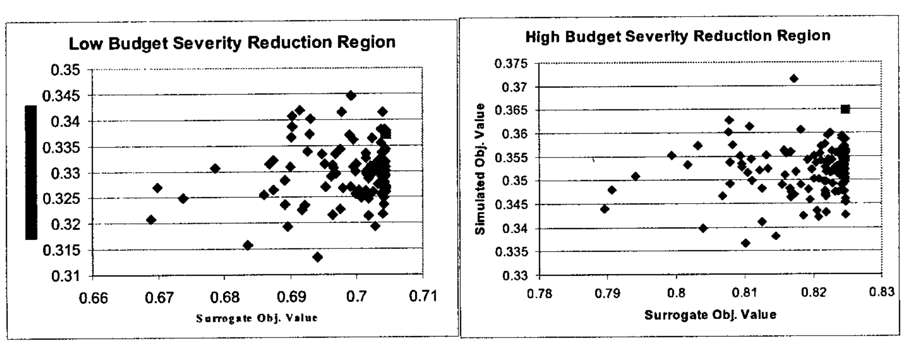

Figure 4.4 Budget Sensitivity about Base Portfolio: Low and High Cost Portfolio Regions.

are shown with two significant digits to demonstrate the lack of precision offered by the simulation. Observe the similarity when all observations of each type are averaged; the only dissimilarity occurs for the $0.05 million category, the category that contains the largest number of observations and the largest number of 0.0% reductions. When seeking to maximize reduction, the lowest reductions are not likely selected; therefore, observe the best single percent reduction observations. It is reasonable to expect significant differences in the greatest reduction achieved by a single control in each cost category, but there is less than 1% difference between four of the five categories. Only $0.5 million controls show increased severity. Nonetheless, selecting at most one control for each type of aircraft would rarely be seen in a portfolio, so the five best controls from each category have been evaluated to indicate their relative severity reduction. The last two columns of the cost-reduction comparison table indicate the percent range of severity reduction to expect for the top five controls. The $200 million category and the $0.05 million category particularly draw attention by indicating that, on one hand, for $1 billion a 10% reduction in severity is possible while, on the other hand, a 10% severity reduction is also possible costing only $0.2 million, when the functions behave as modeled.

Table 4.3 Effectiveness Trends.

Control Cost	Number of Controls	Severity Reduction			
		All Avg	Best	Top 5 Total	Top 5 Avg
$200,000,000	49	0.0044	0.035	0.10	0.020
$ 90,000,000	66	0.0046	0.039	0.15	0.030
$ 19,000,000	87	0.0032	0.036	0.13	0.027
$ 500,000	31	0.0040	0.014	0.057	0.012
$ 50,000	120	0.0019	0.031	0.099	0.020

4.3.1 Cost-Benefit Insights. The analysis examining the similar reduction in severity for controls in significantly different cost ranges reveals the most significant insight to this study. Exhausting a specified budget should not be the objective. The Army Safety Center desires the capability to recommend a "One to Goal list" composed of the number of specific controls it takes to obtain a 50% reduction in severity. To rank the Safety Center's "One to Goal" list, while still accounting for the interactions only revealed by the simulation, expensive controls must be selected as a result of known performance versus

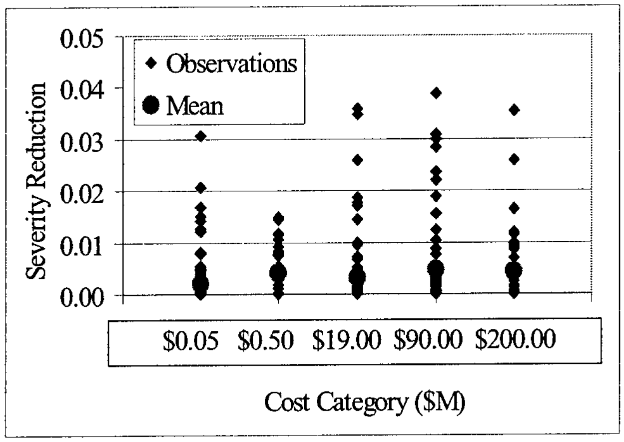

Figure 4.5 Plot of Individual Control Severity Reductions by Control Cost

cost. Rarely would a single $200 million control reduce severity greater than 400 $0.5 million controls, even including decreasing marginal returns. The orders of magnitude difference in cost estimation often complicate selecting the best set of controls.

The actual portfolios observed by this research indicate no statistical difference because of this problem; as an inexpensive control is removed, another replaces it. The final cost of these controls are exactly the same, and even though the severity reduction may be similar, the overall mean cannot change significantly.

4.3.2 Constrained Searching. The previous results indicate a need to examine controls when a tighter budget is specified. The orders of magnitude difference between some control's cost eliminates any ability to capture the sensitivity of the higher cost controls. The small variations in effectiveness between low-cost controls hides any significant improvements from observation. Addition of a constraint limiting the selection controls to those with a certain budget enables the surrogate integer program to search more specifically to identify the best control combinations. The two regions of consideration evaluated separately in the problem include evaluating only controls that cost less than $1 million and evaluating controls that cost more than $1 million. This partition was selected after observing individual control impact on severity reduction; the marginal cost-effective reduction in severity points out extreme disparity between the best single control at $0.05

million, 0.014 $M/\%$, and the top single \$200 million control, 64.5 $M/\%$. The overall cost of all 353 controls examined totals \$17,414,500; controls less than \$1 million make up 43% of the number of controls (151) but less than 1% of the possible total cost (\$21.5M). Generating a new portfolio based on these diverse selection variables involves dividing the decision variables into two sets, the high-cost controls (over \$1 million) and the low-cost ones (under \$1 million). The individual cost sensitivities are extremely different between the problems, therefore, solve the low-cost problem first. Aggregation of the new insights to the current problem provides a new solution with less repetitive control switching.

The large set of possible controls allows a portfolio generation method to distribute funds efficiently to within \$19M of the budget limit, but at this point the remainder of the budget is allocated to inexpensive, and sometimes inefficient, controls. The purpose of this subproblem is to simplify the selection variable set, eliminating less effective controls thereby forcing the remaining budget to be allocated to the more effective controls. The low-cost control integer program introduces a constraint where $\sum C_i \cdot X_i = 0$ for all i with $C_i >$ \$1 million. In addition, the resource constraint for the budget will have an adjusted right hand side with an appropriate range for the low-cost controls, \$2 million to \$10 million. This maximum range is derived by summing the cost of the strongest controls, those with an individual severity reduction greater than 0.001. The method for selecting effective controls enabled the possible control set to be reduced by 77 inexpensive controls.

Analysis of high-cost controls reveals that of the total 202 controls that cost greater than \$1 million, the cost and effort to analyze each alternative and reduce the possible set outweigh the benefit of the results. The integer program effectively selects essential controls to accommodate the size of the control set. Consequently, no additional constraints for high-cost controls have been added to the problem.

4.3.3 Expanding the search to a second base portfolio. Using the constraints generated by the cost-partitioned problem, the integer program recommends a secondary base portfolio. This new potential control set forces the local knapsack search algorithm to select higher cost controls to exchange when finding test portfolios. Eliminating extra-

neous, less effective, controls requires different controls to be interchanged and the local search region expanded. The secondary base portfolio contains 103 controls, which is 56 fewer than the first base portfolio, and observes a mean severity reduction within 1% (less) of the first base portfolio. The cost of the secondary base portfolio is not more than $10 million less than the original base portfolio with budget constraint at $1 billion.

Enabling the local search to incorporate a wider range of controls reveals additional search regions but, most importantly, additional insight into the performance of high-cost controls. The expected percent severity reduction for this region spans 3.5%. No portfolios in this set perform better than the best portfolios at the original base region. The results of this test and sensitivity about this region do not indicate additional tests and exploration are needed.

4.4 Selecting the Optimal Portfolio

The preceding search procedures guide the identification of the recommended portfolio region and bracket a wide range of "good" portfolios. The actual selection of a single portfolio provides some insight into the process. As noted in the previous sections, many portfolios generated similarly to those in this set could represent good, possible options for the decision makers at the Safety Center to examine; however, the real insight from these portfolios focuses on the general response of the system. Single control portfolios evaluated by this simulation tend to return extremely small percent reductions. One of the best observed generated only a 3.5% reduction, that being control H60-C34 (addition of Digital Source Collector (DSC), envelope cueing (exceedences), and notice to pilot of exceedences/crew monitor). Single control portfolios much more frequently return severity reductions around 0.03% such as AH64-C30, acquire crashworthy ERFS (Extended Range Fuel System).

Examining portfolios across the range of budget values displays an increasing Severity Reduction with increasing budget, see Figure 4.6. Unfortunately, as the budget increases, the amount of reduction per dollar spent decreases. Single controls, when applied together as portfolios, display diminishing marginal returns. This finding is important, but not unexpected based on the discussion in Section 3.2.3, because none of these simulated

observations meet the goal of 50% reduction in severity. Previously, ASIST has been able to meet the 50% goal by evaluating controls individually and assuming that every control acted independently of others; the simulation results from this study disagree with that assumption. These results indicate that as additional controls are added, severity decreases at a decreasing rate. The purely additive model does not represent this phenomenon. These diminishing marginal returns suggest that spending an additional $1 billion may not even return a significant decrease in severity. More investigation into this aspect of the problem is needed.

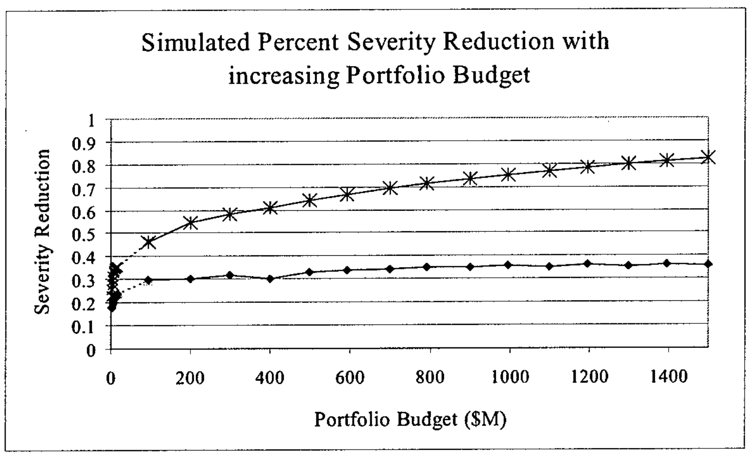

Figure 4.6 Comparison of Additive Severity Reduction and Actual Simulated Severity Reduction

There are two elements to selecting an acceptable portfolio: first, good controls must be selected and second, interactions must be used to achieve maximum reduction. An acceptable portfolio meets all feasibility requirements defined in the constraints of the integer program.

4.4.1 Finding better controls. The results of this analysis of portfolios reveal that individual controls that reduce the most severity effectively reduce the most frequently occurring or the most severe hazards. In a way, the controls that show highest reduction are the controls that best fit the definition of a control: an implemented action that reduces the likelihood or severity of a hazard occurring. The first result should intuitively make sense, to obtain the greatest reduction, fix the problems that occur most often. Control H60-C34

is mentioned above, and this particular high-cost, material-driven solution returned good reduction in severity primarily because it directly reduced AVN-01 hazards which appear 27 times in the accident data set. A possible control may also decrease severity by a substantial amount if, although an specific hazard occurs infrequently, the results of it ever occurring are catastrophic. Note hazard AH64-10, failure of the yellow engine harness can cause the HMU to command the engine power to either underspeed or overspeed resulting in degraded engine performance and possible aircraft damage. This hazard only appears twice in the current accident data set; however, implementation of control AH64-C38, mandatory replacement with new yellow harness, entirely eliminates this hazard. Consequently this single control, has a severity reduction of 1.5%, one of the best 25 individual controls.

If selecting an individual control, note the specific cost, casualty, and frequency contributions of the affected hazard. A single control may only eliminate the severity of cost and leave casualties at the current level. The contribution break down enables a user to figure out what severity issues are reduced by a specific hazard. The affect of different hazards contributing to the same incident leads to the incorporation of multiple controls as a better method for reducing severity.

4.4.2 Finding better portfolios. When evaluating the surrogate objective function to initialize the search region, the result of this additive model indicated that although the coefficients accurately represent single controls, their combined output differed significantly. Each expected severity reduction observed as output of the model under-achieves the projected percent reduction. The combined hazard effectiveness value rationally reduces the effect of two controls acting on one hazard; this is one cause of over estimation. Due to innumerable control combinations, simulation output must be used in conjunction with search methods to find and accurately identify effective control combinations.

The differences between the mean severity reductions that span $100 million through $1.5 billion is approximately 0.05. The 90% confidence interval about the $95 million budget is (0.23, 0.38); the 90% confidence interval about the $1.5 billion portfolio is (0.28, 0.41). These differences arouse interest about the controls contained in the low-cost budget. An analysis of the difference between the 134 controls in the low-cost portfolio

and the 159 controls in the $1 billion portfolio. Note the small difference in the number of controls, closer inspection reveals that the remaining $900 million funds more expensive controls. When these individual budgets are broken down by DOTLMS area, percentage weight of the budget shifts from training controls in the low-cost portfolio to materiel in the high-cost budget.

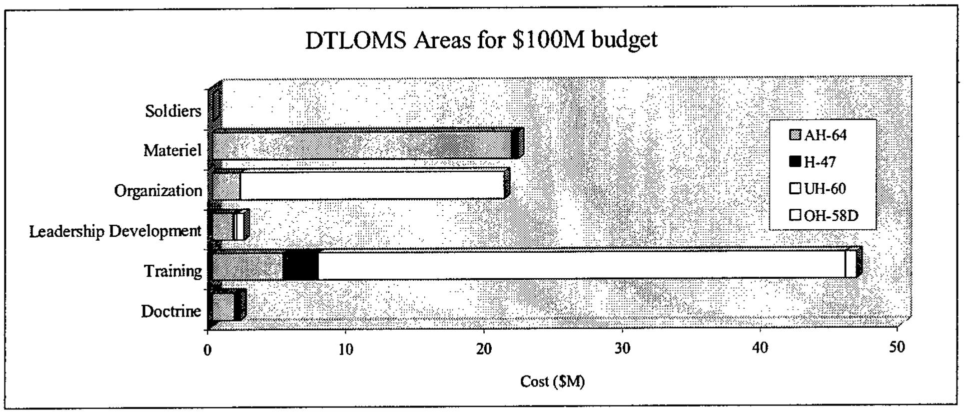

Figure 4.7 Budget Proportions for DTLOMS with a $100M budget portfolio

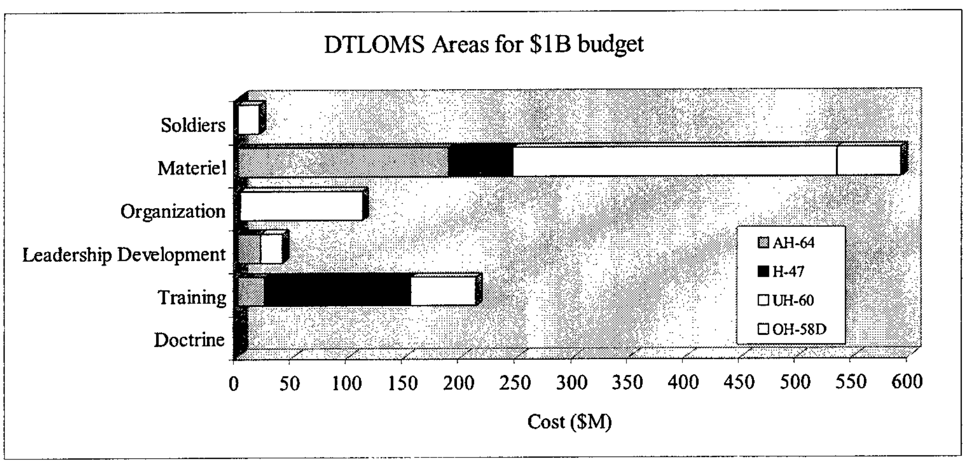

Figure 4.8 Budget Proportions for DTLOMS with a $1B budget portfolio

The cost scale differences are of particular significance, showing the relative differences. From these charts, note the weighty proportion of the cost spent on AH-64 materiel. The UH-60 places demands on the budget for its materiel controls when funds are avail-

able, but under a lower budget uses training to reduce accidents. These bar charts provide insight that a decision maker could use when adapting to changing budget allocations.

4.5 Results Summary

This chapter explored individual controls and the responses of portfolios; both provided insights for decision makers to consider. None of the observed portfolios attained the goal of a 50% reduction in severity; however, the method of aggregating all data into one general set and the conservative method of estimating hazard reduction impacted these results. Based upon the responses attained, the Severity Reduction Simulation suggests a more detailed analysis of the interactions of promising portfolios of controls. It also suggests focusing portfolio selection on a careful examination of low-cost controls within an assumed budget.

V. Conclusions

The Army Safety Center initiated this partnership with AFIT to better analyze and answer one question: *how can we meet the Secretary's goal of a 3σ reduction in accidents*? Since this time, the goal has become more specific, by defining severity, and now asks: *what are the best controls to apply to obtain a 50% reduction in severity*? This research effort integrates several operations research techniques, incorporating the data collected in the Risk Management Information System and the insights of experts and the USASC leadership, to form a process that helps the Army meet their goal. Using decision analysis, Monte-Carlo simulation, linear programming, and search heuristics, the combined methodology demonstrated within this study recommends techniques for the selection of control portfolios. The methodology provided by this research assists the Army Safety Center in accomplishing their mission; it takes a proactive approach to hazard analysis while incorporating risk management tools with the ultimate goal of "preventing the accidental loss of America's most precious resources– it's sons and daughters– and conserving [their] materiel resources" (1).

5.1 Overview of Results

Incorporating multiple analysis techniques into an automated system provides a measure of mean severity reduction for a particular portfolio of controls. These controls, as identified and evaluated by ASIST, decrease the likelihood or severity of an accident. Insights presented in Section 4.2.1 provide ways to interpret the control's effectiveness. Although there are many ways to select particular portfolios from the $2^{353} = 1.8 \times 10^{106}$ possible options, the integer program with surrogate coefficients results in a consistent measure that ordinally represents actual portfolio reductions. Exploring the regions surrounding the base point involves generating many portfolios in the local region. The problem evolved further after a lack of sensitivity to cost was observed; the addition of a constraint limiting the low-cost controls minimized the search region and recommended a slightly different alternative base portfolio. No single optimal portfolio from the multitude of possible controls is recommended, however, regions for reasonable operations can be identified using this methodology. The following sections identify specific criteria for

selecting portfolios and also explain further steps that may enable this methodology to return more specific values.

5.2 Benefit Added by the Research

This research represents the third step of an on-going partnership between USASC and AFIT; portions of this work are an adaptation and enhancement of previous work. The points presented here identify the unique benefits of this work. Previous work addressed the aviation accident severity from a narrower viewpoint; this study takes the first step toward joining multiple systems into a single set for measuring accident severity. The examination of portfolios of controls, used in the search algorithm, clearly points out that the system displays diminishing marginal returns in Severity Reduction with respect to cost. In the course of the effort, errors within H-47 ASIST database were detected, and once these errors are rectified, future efforts will be able to use ASIST CH/MH-47 data as *actual*, rather than just *notional*, data. Increasing the usability of the system was a primary focus early in the effort. At the conclusion of this effort, there exists an automated severity reduction simulation ready to be integrated into @RISK, or another Excel-based simulation software.

Many possible integration standards were considered for combining multiple systems into a more Army-focused model. To aggregate accident severity by system, the primary question is: "what is the best predictor of future accidents, by type?" Hours flown by aircraft type, hours flown per month per aircraft, straight percent composition of the fleet, and actual past accidents are all measures for aggregating accident data. The Safety Center desires the focus to remain at the highest level possible, the Army-focused approach, because the target is an Army-level goal of 50% reduction in severity. To best answer this question, the ASIST-evaluated accident cases were combined into a single set. A Poisson- based random variate generated possible accident numbers, and actual cases were randomly selected as possible accidents. Therefore, the distribution of systems selected are based on the percentage of each aircraft type as represented in the database. Aggregating by this factor implies that future accidents will tend to be distributed, over aircraft types, in the future as the distributions have been in the past (*i.e.*, time-invariant).

The original ASIST implementation of the data found each aviation control value, and ranked the controls, and then considered cost to select the "One to Goal List." This method makes several assumptions, including the additivity of severity reduction. This research demonstrates that when combining controls into a set, if their total reduction is less than the sum of the individual control reductions, a shortfall occurs. Because the Army desires to achieve 50% reduction in severity, particular attention must be afforded to the assumption of additivity of severity. As noted in Section 4.3.1, a comparison of cost versus effectiveness consistently displays diminishing marginal returns. Currently, simulation techniques most effectively incorporate the uncertainty of accident occurrences with the possible types to provide expected ranges for the mean severity reduction. These techniques should be updated as necessary to keep the input current and provide the best model of commander preference and observation.

Using notional data for the ASIST-evaluated information on the H-47 airframe, this study to modeled the complete force-modernized aircraft branch of the Army severity model. Corrected data for the H-47 database is forthcoming; integrating this corrected information involves nothing more than basic spreadsheet manipulation.

Prior to this effort, a good simulation methodology was in place; however, this highly-interactive system required significant man-hours and provided plenty of opportunity for human error. To evaluate portfolios, this research developed a system that takes a distribution, a 0-1 portfolio specifying a set of controls, and its location and returns a mean severity reduction. This system is described in more detail in Appendix B. This *Single_Run* routine was developed to return output that is then used in an @RISK model. Although each simulation takes approximately three minutes to complete, the operator now benefits from significantly shortened set-up processing.

The Safety Center benefits from sponsoring this effort by obtaining a clarified methodology, an improved database, and a more user-friendly system. The Safety Center intends to continue this partnership and further expand this model. There is also the possibility that the Value-Focused Thinking approach may be used across services.

5.3 Insights

Obtaining a high reduction in severity, specifically a reduction greater than 40%, is extremely rare using this model with the current data set. Because the Army seeks to reduce severity by at least 50%, this is a significant problem. A hypothesized reason for the sub-standard reduction in severity comes from the actual Severity of Losses values returned by each individual repetition within an iteration. The individual repetition calculates a Severity of Losses for the randomly selected accident data, then it applies the selected controls and obtains the new Severity of Losses. The percent difference in these values is the actual percent severity of losses. Although this method of calculation returns the specific desired metric, the actual measured Severity of Losses values are lost in the calculation. A few selected runs reveal the actual Severity of Losses for the extreme cost portfolios: a high-cost portfolio provided a score of 0.08 *severity*, while a low-cost portfolio averaged 0.13. These portfolios expected a mean severity reduction between 0.12 and 0.24, for the low-cost portfolio and between 0.37 and 0.49 for the high-cost portfolio. A single block of 100,000 flight hours is generated 26 times per iteration, for the approximately 2,600,000 flight hours in 5 years for the force-modernized aircraft in the study. The simulation from these 100,000 hour blocks provides the 90% confidence intervals covering the expected percent severity reduction.

The current framework gives commanders a multitude of possible portfolios from which to select. Although the Safety Center originally identified controls while ignoring the cost, at some point in the selection process cost must become a factor. When observing actual full portfolios, there are many factors to consider such as the airframes affected, the DTLOMS areas addressed, and the cost allocation. The tabular data presented in Figures 5.1 and 5.2 show a single portfolio broken down into significant parts.

This table displays many of the issues that a commander must take into consideration when selecting a portfolio from a set of similar-return options. Due to the overlapping confidence intervals about the mean severity reduction for portfolios from $100 million to $1.5 billion, the Army must choose how to allocate their funds. If portfolios differing by $1 billion likely return comparable reductions, the Army could decide to request the smaller budget control portfolio and have a better likelihood of receiving funding.

DTLOMS	AH-64	235.9	CH/MH-47	188.6	UH-60	493.7	OH-58D	77.5
	AH64-C09	0.5	H47-C41	0.05	H60-C03	0.05	OH58-C16	0.05
DOCTRINE	AH64-C13	0.5	H47-C42	0.05	H60-C35	0.05	OH58-C55	0.05
	AH64-C24	0.5	H47-C44	0.05			OH58-C21	0.05
	AH64-C29	0.05	H47-C50	0.05				
	AH64-C57	0.05	H47-C79	0.05				
	AH64-C10	0.5	H47-C01	0.05	H60-C06	19	OH58-C09	0.05
TRAINING	AH64-C11	0.5	H47-C03	90	H60-C07	19	OH58-C11	0.05
	AH64-C12	0.5	H47-C06	19	H60-C09	19	OH58-C14	0.05
	AH64-C39	0.05	H47-C101	0.05	H60-C18	0.05	OH58-C22	0.05
	AH64-C46	0.5	H47-C102	0.05	H60-C19	0.05	OH58-C24	0.05
	AH64-C50	0.05	H47-C114	0.05	H60-C22	0.05	OH58-C34	0.05
	AH64-C52	0.05	H47-C121	0.05	H60-C37	0.05	OH58-C52	0.05
	AH64-C55	0.5	H47-C122	0.05	H60-C41	0.05	OH58-C56	0.05
	AH64-C58	19	H47-C124	0.05			OH58-C59	0.05
	AH64-C59	0.5	H47-C131	0.05			OH58-C62	0.05
	AH64-C60	0.5	H47-C136	0.5			OH58-C63	0.05
	AH64-C61	0.5	H47-C137	0.05			OH58-C64	0.05
	AH64-C62	0.5	H47-C18	0.05			OH58-C70	0.05
	AH64-C63	0.5	H47-C22	0.05			OH58-C71	0.05
			H47-C25	0.05			OH58-C74	0.05
			H47-C30	0.05			OH58-C76	0.05
			H47-C40	0.05				
			H47-C43	0.05				
			H47-C47	0.05				
			H47-C53	0.5				
			H47-C55	0.05				
			H47-C65	0.05				
			H47-C66	0.05				
			H47-C67	0.05				
			H47-C69	0.05				
			H47-C72	0.05				
			H47-C73	0.05				
			H47-C74	0.05				
			H47-C76	0.05				
			H47-C77	0.05				
			H47-C80	0.05				
			H47-C81	0.05				
			H47-C90	0.05				
			H47-C91	0.05				
			H47-C93	0.05				
			H47-C96	0.05				
			H47-C12	19				

Figure 5.1 An Actual Portfolio of Controls, Categorized by Airframe and DTLOMS Area (part 1)

DTLOMS	AH-64		CH/MH-47		UH-60		OH-58D	
LEADERSHIP DEVELOPMENT	AH64-C19	0.5	H47-C51	0.05	H60-C05	19	OH58-C30	0.05
	AH64-C95	0.5	H47-C99	0.05	H60-C12	0.05	OH58-C35	0.05
	AH64-C96	19			H60-C13	0.05	OH58-C51	0.05
	AH64-C97	0.5			H60-C40	0.05	OH58-C53	0.05
					H60-C42	0.05	OH58-C54	0.05
					H60-C43	19	OH58-C57	0.05
							OH58-C67	0.05
							OH58-C77	0.05
							OH58-C66	0.05
							OH58-C72	0.05
ORGANIZATION	AH64-C40	0.5	H47-C118	0.05	H60-C01	19		
	AH64-C43	0.5	H47-C28	0.05	H60-C08	90		
	AH64-C44	0.5			H60-C38	0.05		
	AH64-C64	0.5						
MATERIEL	AH64-C02	0.05	H47-C07	19	H60-C16	90	OH58-C29	0.05
	AH64-C03	19	H47-C08	19	H60-C30	90	OH58-C02	19
	AH64-C15	0.5	H47-C09	0.05	H60-C44	90	OH58-C08	19
	AH64-C21	90	H47-C116	0.05	H60-C47	19	OH58-C44	19
	AH64-C23	19	H47-C13	0.05				
	AH64-C35	0.05	H47-C133	0.05				
	AH64-C36	19	H47-C14	0.05				
	AH64-C38	0.5	H47-C17	19				
	AH64-C49	19	H47-C23	0.05				
	AH64-C54	0.05	H47-C45	0.05				
	AH64-C56	19	H47-C58	0.05				
	AH64-C70	0.5	H47-C59	0.05				
	AH64-C74	0.5	H47-C64	0.05				
	AH64-C79	0.5						
SOLDIERS			H47-C119	0.05	H60-C02	0.05	OH58-C31	19

Figure 5.2 An Actual Portfolio of Controls, Categorized by Airframe and DTLOMS Area (part 2)

5.4 Future work

The model framework presented in this analysis is supported by the necessary theory; however, the desirable recommended numerical results do not appear. In any input-output process, careful examination to ensure the process uses good input yields the promise of improved output. These recommendations for future work focus on improving the input data.

Better estimates of severity would go a long way to improve results. To better illustrate what severity looks like for each airframe, specialized severity functions will increase the precision for severity in 100,000 flight hours. A possibility for this is to consider severity functions that incorporate a severity value of 1.0 within the range of values (see Figure 5.3). As with any decision analysis study that incorporates Value-Focused

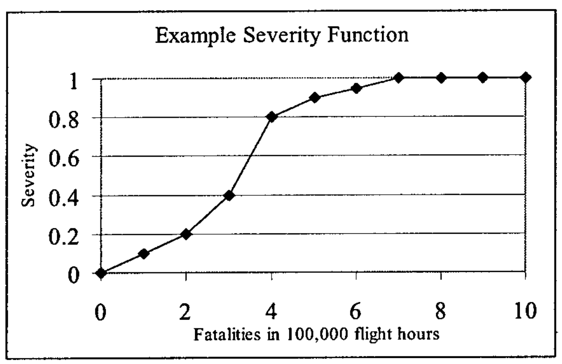

Figure 5.3 Example Evaluation Measure

Thinking, the commander's preferences need to be updated to include the preferences of the most senior level decision maker. Particularly in the case of these ever-changing accident-based evaluation measures, a point must be made to reflect the Army's current goals and values.

Controls, although designed to address *specific* hazards, may in fact impact other, similar hazards. The hazards and associated controls currently in use have all been developed by airframe. This entire research effort, as well as on-going Army aviation safety decisions, are based entirely on this set of data. The suspected synergistic interplay between controls and hazards, along with any resultant severity reduction (as first pointed

out in Section 3.3.1), may provide additional insights as to where to most effectively spend the safety budget, leading to better safety decisions. It is worth noting that intial observations from this research indicate that overlap in hazard occurrence, and hence overlap in controls designed to mitigate those hazards, lead to an overall *smaller* than additive severity reduction.

By defining a better hazard and control taxonomy, elimination of redundant hazards and combining overlapping controls would serve to make the search region more compact. This feature enables significant hazards and controls to be highlighted. Currently a pilot study exists that addresses the hazards associated with tree-strikes. Apply the analyst's current test case as an example of how although ASIST evaluated them well, combining them as much as possible to create more robust controls and hazards will make the program in general better. Better input yields better output.

As with any analysis, the more precise the input, the less the uncertainty of the output. For this study, ASIST identified controls without regard for the possible cost of implementing these. Decision makers will definitely consider cost as a factor; the better the cost estimates, the more realistic these portfolios of controls can be. Because the current estimates are only measures of magnitude, it is important to refine the cost estimates to better budget controls.

There is potentially a need for additional research to normalize the systems based on something other than flight hours because the likelihood of accidents is not based on use, but also on type of use.

5.4.1 Expanded Applications. This study, although it specifically addresses Army aviation, has many applications for other services as well as the aviation industry. The safety community commonly categorizes conditions and correction factors into *hazards* and *controls*. By incorporating the severity measure, identifying hazards and controls, and evaluating severity reduction, this methodology expands a framework that may be used on multiple other systems. The effort to modify thinking to address *severity*, rather than accident rate, will help the related safety organizations to identify their primary concerns under multiple competing objectives for quantifying severity of accidents. Support for

severity as a measure has been developed in other sectors of safety research to include (28). This view of accident safety enables leaders and commanders to make better decisions by evaluating the effectiveness of controls in reducing accident severity.

Adding the evaluation of all accident cases in terms of hazard conditions, as the Army is now proposing, prepares the service to select controls by this quantitative and qualitative method. The Federal Aviation Administration has pursued accident safety with a hazard focus in their 1998 study "Safer Skies: A Focused Agenda" which identified the important factors in accidents (12). Their approach successfully identified focal issues for commercial aviation safety; studing possible controls and a quantitative estimation of effectiveness is the next logical step. This expanded case study for the Army Safety Center shows how hazard and control data, a severity value model, and a simulation can be used with heuristic techniques to select sets of controls to apply for the reduction in aviation accident severity.

As the U.S. Air Force also seeks to improve its safety, this methodology takes the focus off of possible alternatives and places it on reducing the important factors affecting aviation accident severity. The Army has integrated multiple rotary wing systems to obtain a single overall severity reduction measure; likewise, the Air Force can use safety publications to establish a multiple objective accident severity model and evaluate its systems. The integration of bootstrapping using simulation and portfolio selection based on an initial surrogate objective function with associated extrapolated regions allows commanders to look at the alternatives as evaluated based on their achievement of the goal: severity reduction.

5.5 The Finale

The methodology provides a defensible way that individual controls may be prioritized. However, overall accident interactions cannot be simply quantified using an additive model, a simulation technique best incorporates the uncertainty. The audacious goal that the Army set may be achievable for individual aircraft; however, this study reveals that an exorbitant amount of funds would likely not consistently produce the desired results

overall. Finally, improvements made to individual parts of the model to better estimate inputs can only result in improved recommendations and possible portfolios.

Appendix A. Severity Functions

The support for the severity evaluation measures are developed in Chapter III; this appendix develops the single dimensional severity functions for each evaluation measure. A single dimensional *value* function is constructed such that the preferred level receives a 1, and the least preferred level receives a 0 (19:61). Working with the Army Safety Center, severity is modeled similarly; however, the least severe situation is most desirable, receiving a zero. Likewise, the most severe accident situation is least desirable, receiving a one. This description is clearly understood and supported by the leadership at the Safety Center. The following description of individual value function ranges are based on simulation, the shape of the curves are based on interviews with experts, and the final overall approval given by the ORSA Division Chief, MAJ Sperling.

At the time of elicitation, the following officers at the Safety Center provided input in the area of their expertise for the Severity functions. *Casualties* and *total costs* severity functions were developed with COL Warren, USASC Deputy Commander. *Unit readiness* severity functions were developed with prior battalion commander, LTC Semmens, USASC Executive Officer. Finally, LTC Gleisberg, USASC Judge Advocate General developed the *environmental damage* severity functions because of his background in environmental law. In order to obtain a worst case range estimate, ten thousand simulated blocks of 100,000 flight hours were observed to find the maximum range for each measure.

A.1 Casualties

The following severity functions use Army officers' preferences and Army accident data to assess the severity of casualties for 100,000 flight hours in the selected Force Modernized Aircraft.

A.1.1 Loss of Life. The loss any soldier is tragic. Adequately quantifying the severity of a lost life is extremely difficult. COL Warren expressed that, to the Army, each soldier is equally important. A linear relationship between lives lost and severity best describes the Army perspective (13:30).

From observation of the fatalities present in the data addressed by ASIST, slightly less than 2 lives lost per 100,000 flight hours is expected. Simulation shows an expected maximum observable number of fatalities for 100,000 flight hours to be 23. Consequently the range of incidents for fatalities in 100,000 flight hours is 0 to 23 fatalities in 100,000 flight hours for the Force Modernized Aircraft.

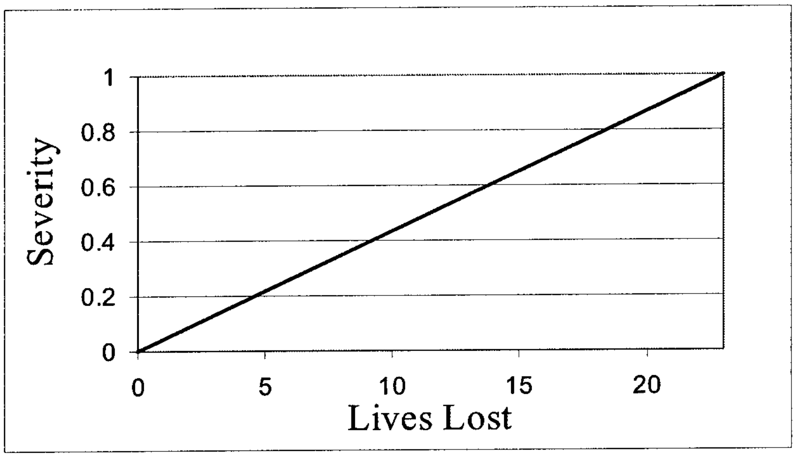

Figure A.1 Severity Function of Evaluation Measure - Fatalities

A.1.2 Permanent Total Disabilities. Permanent total disabilities occur very infrequently. In fact, there are no observed cases of permanent total disabilities for the AH-64, the H-47, the OH-58D and the UH-60 during FY94 through FY98. Occurrences of this type of casualty did occur in other airframes during this time period, and they have occurred in incidents involving the force modernized aircraft during different periods of time. For the value model, the necessary evaluation of the severity function is based on preferences and experience of commanders. Noting the severity of a single permanent total disability at 0.75, an increase of each additional total disability is linear. The range for permanent total disabilities is 0 to 6 permanent total disabilities based on historical data in other time periods.

A.1.3 Permanent Partial Disabilities. This severity function captures the impact of permanent partial disabilities. Similar to the tragic incidence of loss of life, an occurrence

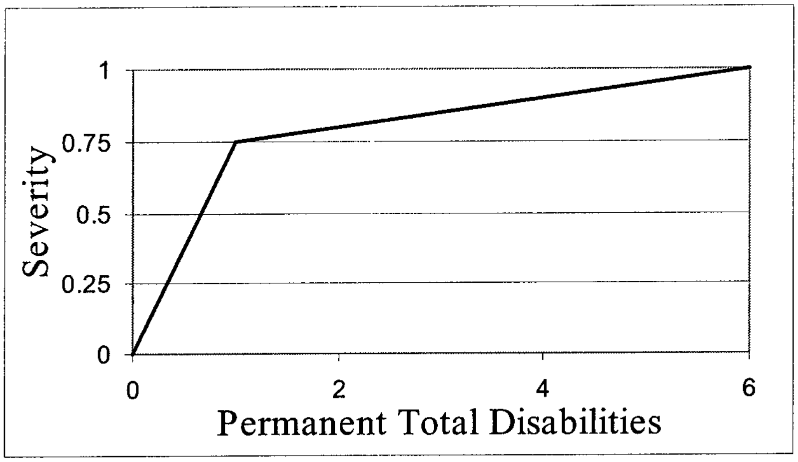

Figure A.2 Severity Function of Evaluation Measure - Permanent Total Disabilities

of permanent partial disabilities effectively causes the Army to lose a soldier. The inability to serve in the same capacity is felt by the Army, and each permanent partial disability that occurs is equally as severe in the judgement of the Army (13:31). The ASIST data does contain occurrences of this type of casualty and its severity is based on a range of 0 to 4 permanent partial disabilities.

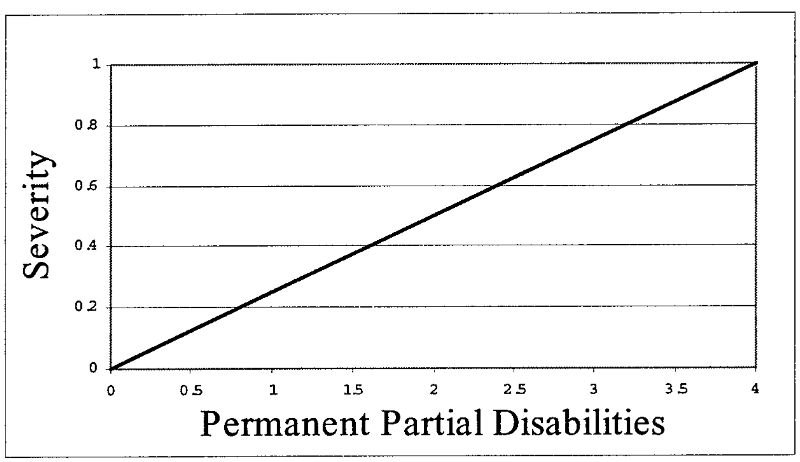

Figure A.3 Severity Function of Evaluation Measure - Permanent Partial Disabilities

A.1.4 Time Incapacitated. To measure the loss the Army experiences from a single injured soldier, time incapacitated is scored in terms of the total days soldiers spend

in the hospital as a result of accidents. The Army views each day hospitalized as equally severe; a linear response describes the relationship between days hospitalized and severity (13:31). The accident data and simulation suggest the range for time incapacitated to be 0 to 153 days of hospitalization for 100,000 flight hours.

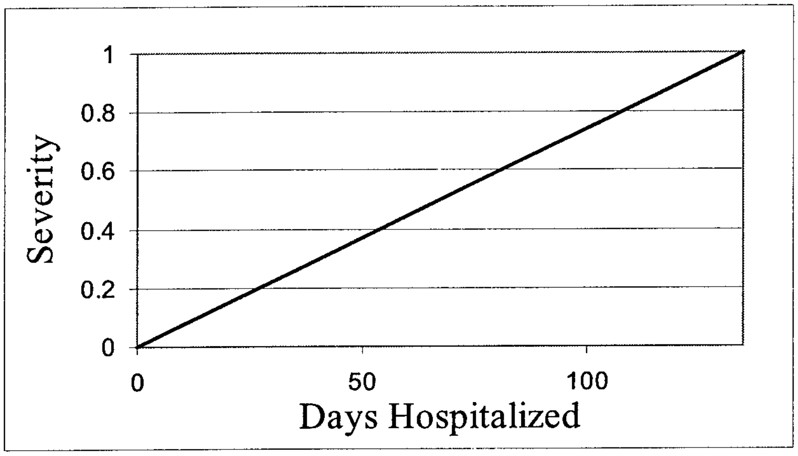

Figure A.4 Severity Function of Evaluation Measure - Time Incapacitated

A.2 Unit Readiness

The severity functions that evaluate unit readiness focus on the battalion level. Evaluating the impact of accidents on a single unit's readiness means developing the impact that accidents have on training execution, unit morale, and equipment availability. Because the model evaluates severity for 100,000 flight hours for the force modernized aircraft, no distinction is made between the types of units the aircraft belong to. This enables us to focus on Army impact while addressing unit issues. The information that these severity functions are based upon was elicited from LTC Semmens, a prior aviation battalion commander. This input provided excellent guidance for relative relationships to severity concerning the issues impacting a unit. Consequently, his input is used as a guide, no specific data points were elicited; future expanded studies should ideally include a complete elicitation from a group of battalion commanders (13:32).

A.2.1 Training Execution. As accidents within a unit increase, a commander may reduce the training frequency, complexity, and realism in an effort to reduce additional accidents. This measure combines the number of accidents that happen within a unit and the class of those accidents. A battalion commander may tend to be more or less risk averse depending on the class of the accidents. It is estimated that he would be as risk averse for three class C accidents as he would be for one class A accident. The following provide a scale for measuring one accident of the specified class (13:33):

- Class A accident = 3
- Class B accident = 2
- Class C accident = 1

The category for evaluation is determined by accounting for the class of the accident multiplied by the number of occurrences within the unit. For example, if a certain unit had two accidents in 100,000 flight hours, one class A accident and one class B accident, the training execution category would be 5. If another unit had two class C accidents, the training execution category would be 2. The severity assigned to each category can be seen in figure A.5. The largest increase occurs between categories 2 and 4. This indicates that a commander would be slightly risk averse if a single class C or class B accident occurred in their unit; however, if a class A accident or multiple class B and class C accidents occurred, the commander would likely become more risk averse. The result of his risk aversion is a reduction in training execution, consequently more accidents and the higher the class of those accidents within a single unit the greater the severity. Little increase in severity occurs above category 6 because it is assumed that a commander would, by this point have already reduced training dramatically (13:33).

The range of categories, 0 to 9, is based on simulated likely combinations of accident classes and amounts.

A.2.2 Unit Morale. Unit readiness is affected by unit morale. High morale often results in better work and fewer accidents; as unit morale degrades, unit readiness

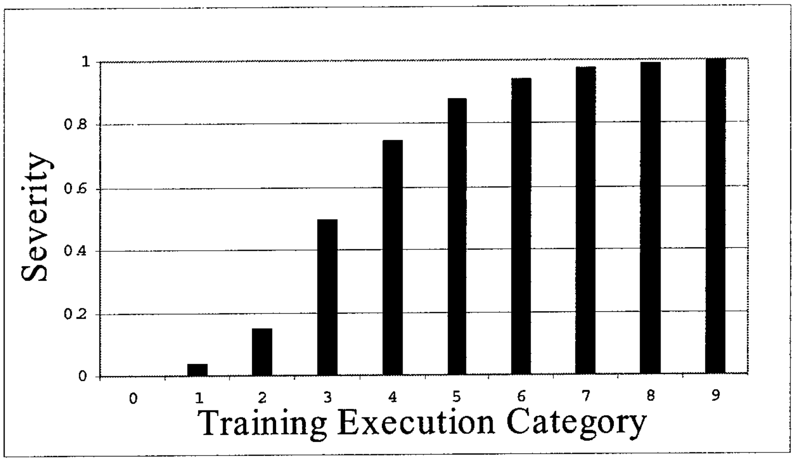

Figure A.5 Severity Function of Evaluation Measure - Unit Training Execution

decreases. Within this analysis, unit morale is made up of two parts, lives lost in unit and magnitude of injury.

A.2.2.1 Lives Lost in Unit. The severity function for lives lost in unit is difficult due to significant differing opinion among commanders. Using Monte Carlo simulations of the model, it was found that 9 fatalities in a single unit for 100,000 Army flight hours is extremely rare, but possible. A few lives lost in a unit is extremely difficult, but manageable. However, the general feeling is that each increasing life lost would affect a unit by an increasing amount. This measure evaluates the impact on morale; it does not indicate the relative importance or value of life (13:34).

A.2.2.2 Magnitude of Injury. The measure magnitude of injury approached unit morale from the perspective of the survivors of an accident, the soldiers whose lives were spared. Because level of injury is difficult to quantify, the standard for evaluating the category follows:

Table A.1 Injury Category Classification

Category 0:	No injuries requiring hospitalization
Category 1:	Injuries requiring $\leq$ 7 days hospitalization
Category 2:	Injuries requiring $>$ 7 days hospitalization, no permanent disabilities
Category 3:	Injuries resulting in permanent disabilities

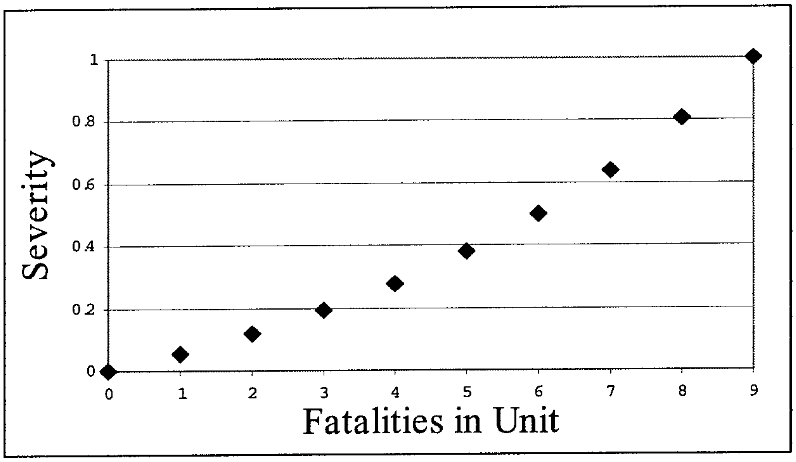

Figure A.6 Severity Function of Evaluation Measure - Lives Lost in Unit

Severity for these categories is based on the impact fellow soldiers' injuries have on unit morale. A brief stay in the hospital has no significant impact on unit morale. Slightly more severe injuries that require a long hospital stay may decrease the morale and the severity for category 2 is approximately two times the severity of category 1. Finally, the most severe injuries are the ones resulting in permanent disabilities. Soldiers being injured this severe on duty tend to be remembered by the remaining soldiers in the unit (13:35).

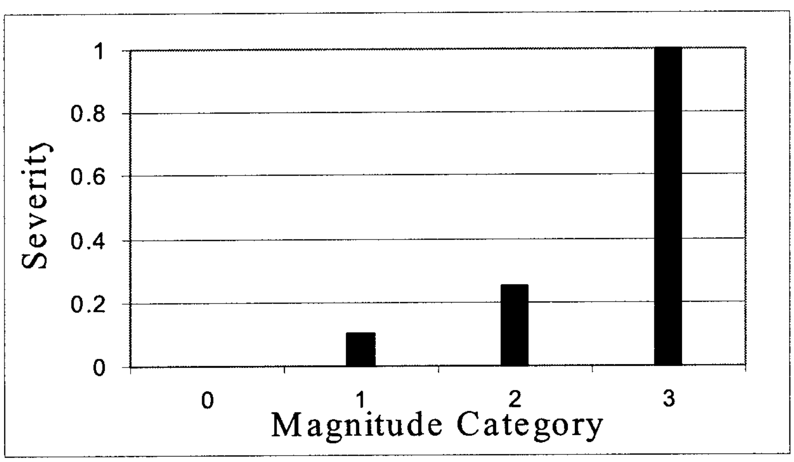

Figure A.7 Severity Function of Evaluation Measure - Magnitude of Injuries in Unit

A.2.3 Equipment Availability. In this case, aircraft alone are the type of equipment that is addressed. Aircraft are deemed unavailable if an accident renders them a total loss, meaning they are not economically repairable, or if they require more than 40 hours of maintenance to repair. Using Monte Carlo simulation and the ASIST accident data, the expected range of unavailable aircraft in one unit is 0 to 3. Because typical units may begin to feel the most impact after the loss of two aircraft, the largest increase in severity occurs between the unavailability of two and three aircraft (13:36).

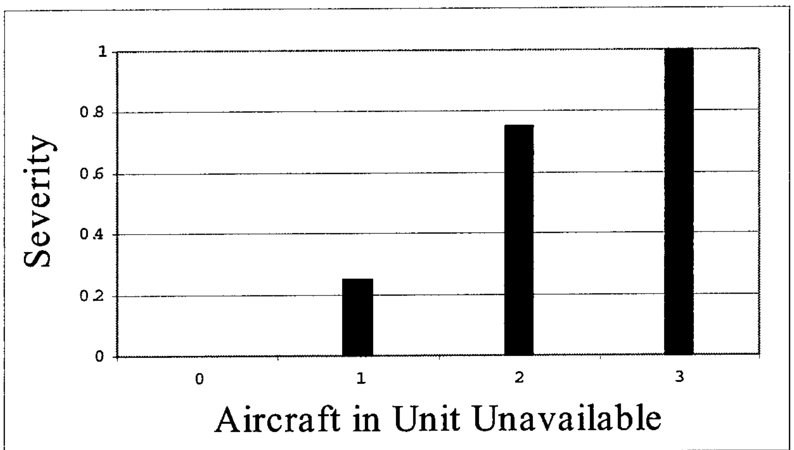

Figure A.8 Severity Function of Evaluation Measure - Available Equipment, Aircraft

A.2.4 Total Costs. The investigative team evaluates the accidents in terms of the dollar cost to the Army. Total Costs include repair or replacement of the damaged aircraft, cost of injuries and hospitalizations, and damage costs. The ASIST data enables the use of Monte Carlo simulation to find the largest possible cost for 100,000 Army flight hours. When assessing the severity of dollars, each dollar is equally important, a linear relationship applies. The range for total cost is \$0 to \$99 million; as total cost increases, severity increases (13:37).

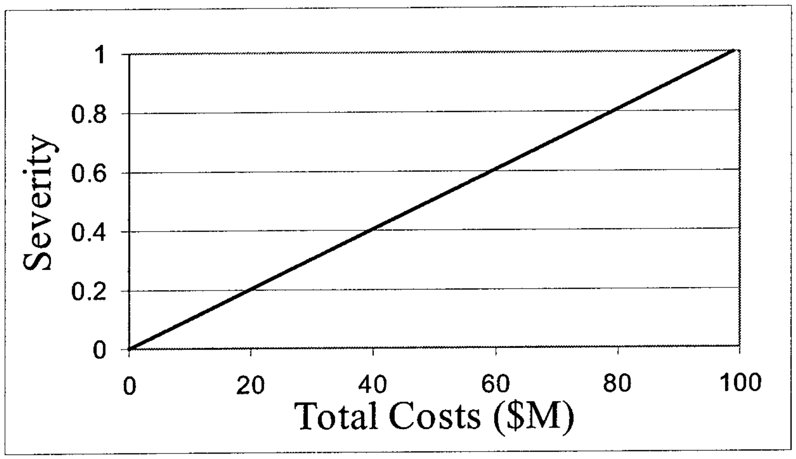

Figure A.9 Severity Function of Evaluation Measure - Total Costs

A.3 Environmental Damage

Currently accident investigations estimate spillage using categories, listed below. The ranges for the categories are the same for all hazardous fluids: fuel, hydraulic fluid, and oil (9:2-11).

Table A.2 Hazardous Fluid Spills Classification

Category 0:	No hazardous fluid spilled
Category 1:	Less than 1 gallon of hazardous fluid spilled
Category 2:	More than 1 gallon, but less than 2 gallons
Category 3:	More than 2 gallons, but less than 10 gallons
Category 4:	More than 10 gallons, but less than 20 gallons
Category 5:	More than 20 gallons spilled

When evaluating the environmental damage occurring in 100,000 flight hours, use the category of the maximum spillage occurrence. This worst-case evaluation estimates the environmental damage severity conservatively.

A.3.1 Soil Damage. Spillage and damage to the soil is assessed by the amount spilled, using the previously defined categories. Currently LTC Gleisburg expressed little difference between the types of hazardous fluid spilled into the soil. Fuel, oil, and hydraulic

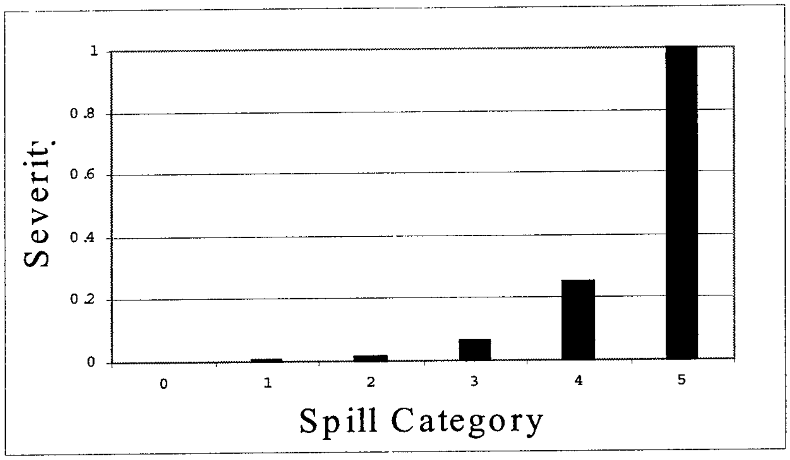

Figure A.10 Severity Function of Evaluation Measure - Spills in Soil: Fuel, Oil and Hydraulic Fluid Damage

fluid all have the same severity function. A category 5 spill was estimated to be 3 times as severe as a category 4 spill, see Figure A.10 (13:39).

A.3.2 Water Damage. Water damage requires different severity functions based upon the interaction of the hazardous fluid and water. Fuel dissipates very easily in water; small quantities are negligible, large quantities can be very damaging. Hydraulic fluid and oil both remain near the surface and do not dissipate in the water, smaller quantities may be slightly more damaging than small amounts of fuel. Two separate severity functions have been developed. For evaluating fuel damage in water, a category 5 spill is 10 times as severe as a category 4 spill, as described in Figure A.12. When evaluating hydraulic fluid and oil in water, a category 5 spill is only 3 times as severe as a category 4 spill, as described in Figure A.11 (13:40).

A.4 Severity of Losses Model Weights

After obtaining the severity functions, preferences between the measures are examined using swing weighting techniques. The leadership of the Safety Center that evaluated the Severity of Losses placed most importance on casualties and secondly on unit readiness. Specifically, fatalities contribute the most to the severity of a block of accidents.

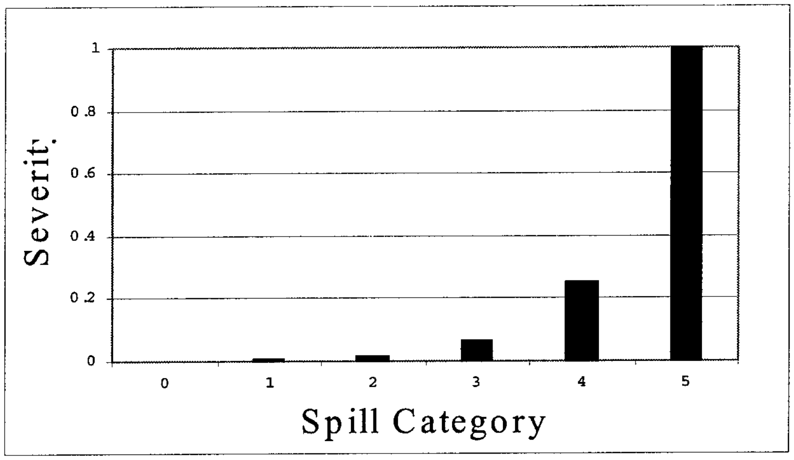

Figure A.11 Severity Function of Evaluation Measure - Spills in Water: Oil and Hydraulic Fluid Damage

Accidents lowering the training execution and consequently reducing unit readiness was weighted second most heavily. Note the minimal weight on environmental damage. This objective is included because it is very important to the Army; however, at this point in time, the Safety Center does not have the data available to accurately account for its contribution.

For a more detailed description of both the severity functions and the elicited weights, reference Gallan, 2000 or Sperling, 1999.

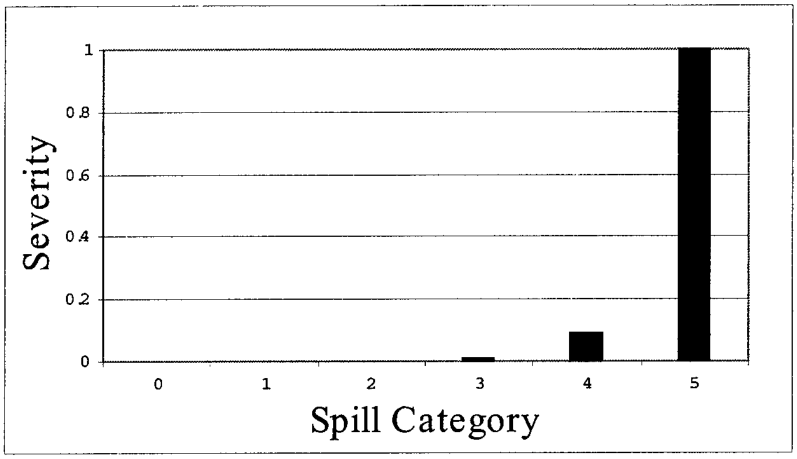

Figure A.12 Severity Function of Evaluation Measure - Spill in Water: Fuel Damage

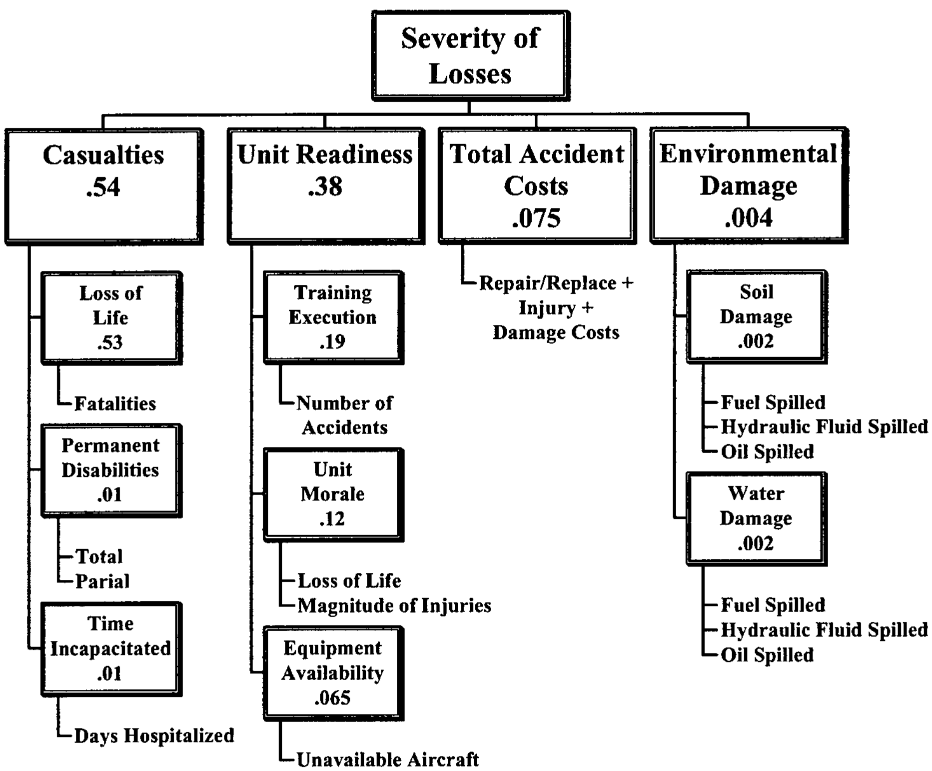

Figure A.13 Severity of Losses Global Weights

In order to follow the code, it is first necessary to understand the basic framework behind what is occurring. This appendix with begin with a general overview of what occurs. It will follow with an in-depth explanation of how the code executes this framework, including references, by name, to the macros and functions used.

For each portfolio to be analyzed, the {0, 1} portfolio of controls model is examined. It finds the hazards reduced by these controls and creates hazard and effectiveness lists. These lists are inputs to the main macro that drives each iteration. The iterations randomly select a certain number of possible accidents to occur. The accidents are then randomly drawn from the accident database. Because each accident has associated hazards that cause the accident or increase its severity, by applying controls that decrease the severity, we see can gain an approximate decrease in severity that the controls supply. The severity reduction is recorded for each iteration. The multiple runs provide a data set from which the expected value of a portfolio can be obtained. The expected values become the inputs for the direct search optimization procedure. Figure B.1 represents the functional flow of calculations within the simulation.

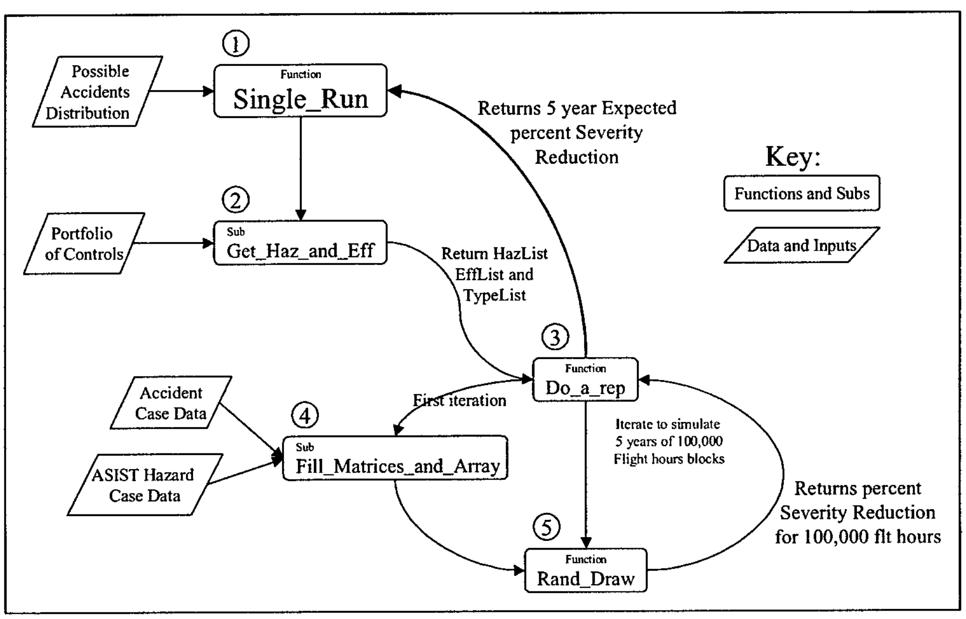

Figure B.1 An Overview of the Severity Reduction Simulation

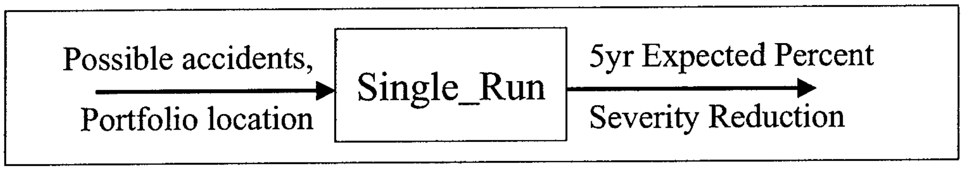

Figure B.2 Function Single Run Input and Output

B.0.1 A single iteration. Prior to beginning any simulation, the following data must be located in worksheets within in Army_FMA_Data.xls:

1. Normalized hazard contributions in "NormAnalysisGroupData"
2. Accident investigation by case number (all types of aircraft) in "AccidentData"
3. Evaluation measure ranges and functions in "EvalMeasuresValues"

The individual hazard assessments for each aircraft are divided by aircraft type into the worksheets AH64_Data, H47_Data, OH58D_Data, and UH60_Data. Within each worksheet, matrices contain hazard assessments, by case number, for Casualties (1), Cost (2), Frequency (3), and Prevention (4). Individual data matrices for each aircraft contain three dimensions: case number, hazard identifier, and the number 1 through 4 representing the type of hazard assessment, as noted above. This data as generated by the accident investigation teams and evaluated by ASIST is the foundation for this entire study. For reference, it is important to note that the H47 information is notional and should be updated before any decisions are based on this study.

The function Single_Run acts as the parent function called by @RISK and itself calling the remaining functions and subroutines. Ultimately, the objective of this function is to take in the distribution of the possible accident rate and to produce a 90% confidence interval for the range of reduction possible by using the specified portfolio.

Single_Run calls the subroutine Get_Haz_and_Eff to obtain the hazards and effectiveness of the portfolio of controls.

Single_Run also calls the function Do_A_Rep which returns the average percent severity reduction of a set of runs representing 26 blocks of 100,000 flight hours, or five years of FMA flight.

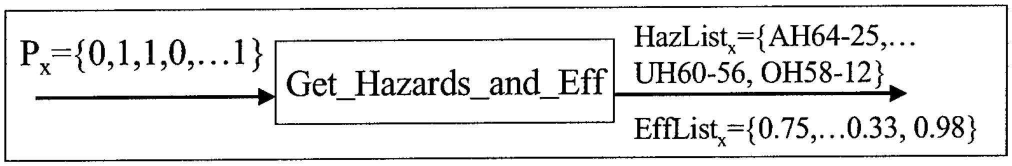

Figure B.3 Subroutine Get Hazards and Effectiveness Input and Output

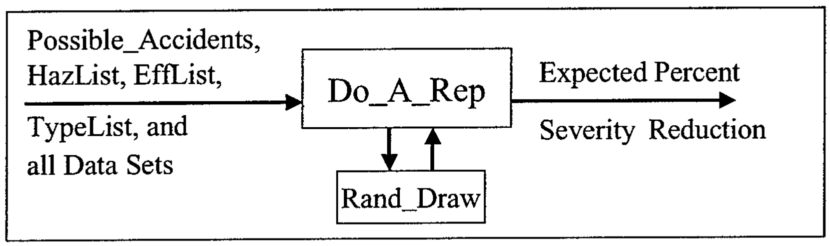

Figure B.4 Function Do A Replication Input and Output

Function Do_A_Rep calls Fill_Matrices_and_Arrays which takes the given aircraft data from the individual workbooks and stores all of the data in dimensioned matrix form in the program's memory. This procedure increases the speed of processing information. Fill_Matrices_and_Arrays is only called for the first iteration of Do_A_Rep; all subsequent iterations recognize the data in memory and proceed with calculations.

Do_A_Rep performs iterations obtaining the percent severity reduction for single observations of blocks representing 100,000 flight hours. The force modernized aircraft addressed by this study flew over 550,000 flight hours in FY2000. The number of hours flown during FY94 through FY98, sum to over 2,500,000 flight hours. By simulating 26 blocks of 100,000 flight hours, a mean severity reduction for the 5 observed years can be obtained. In order to simulate these blocks, Rand_draw must be called.

The objective of this function is to take a random sample of possible accidents and test the improvement gained by applying a certain portfolio of controls. Of all possible

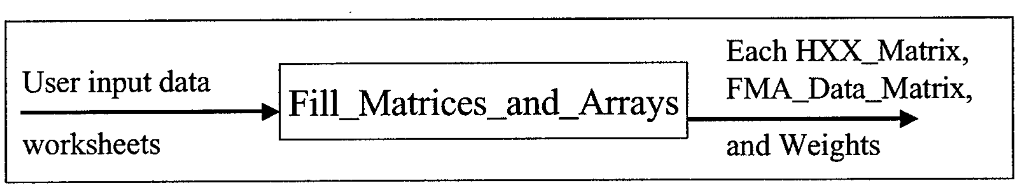

Figure B.5 Subroutine Fill Matrices and Arrays Input and Output

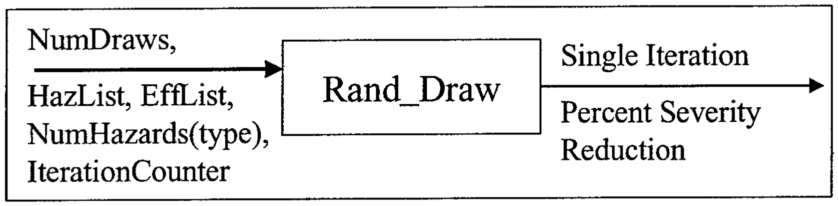

Figure B.6 Function Random Draw Input and Output

accidents, the specified number are selected, the effectiveness applied and the severity score calculated with and without new controls. The percent difference between these severity scores is the value returned to Do_A_Rep.

Do_A_Rep takes the single severity reduction observations and averages them to obtain a value, the mean severity reduction, to return to Single_Run. The value obtained from this simulation is used by the optimization.

This spreadsheet tool has user-friendly macros that will enable the sponsor to format their data an use this simulation technique in the future.

Appendix C. Control Lists for Force-Modernized Aircraft

The following controls were defined by ASIST to reduce hazards for the following aircraft.

Table C.1 Abbrevations for Control Lists

Abbreviation	DTLOMS Area
org	organization
trg	training
ldr dev	leadership development
doct	doctrine

C.1 Control List for the AH-64 Apache

CONTROL	CONTROL STATEMENT	DTLOMS	COST
AH64-C01	Modify force trim switch (no off position).	Materiel	Low
AH64-C02	Amend –10 warning.	Materiel	Nil
AH64-C03	Retrofit ECP0887 (cyclic bellcrank counterweights).	Materiel	Low
AH64-C04	Mechanical Stop tied to Squat Switch (operative during shutdown)	Materiel	Medium
AH64-C05	Improved flight control system (ACAH+ Hover hold).	Materiel	Medium
AH64-C06	Second generation FLIR.	Materiel	High
AH64-C07	Obstacle/wire/ground proximity warning device.	Materiel	High
AH64-C08	"Family of Virtual Rotor Disk/Prox Warning System"	Materiel	
AH64-C09	Revisit external stores jettison protocols and restrictions	Doctrine	VLow
AH64-C10	Develop, monitor and evaluate a Crew Coordination Sustainment Training program integrated into all aviation tasks	Training	VLow
AH64-C11	Standardized multi-aircraft mission abort	Training	VLow
AH64-C12	Hands on inadvertent IMC Training either in the simulator or aircraft	Training	VLow
AH64-C13	Pre-brief on inadvertent IMC contigency	Doctrine	High
AH64-C14	Increase Flying Hour Program	Org	VLow

CONTROL	CONTROL STATEMENT	DTLOMS	COST
AH64-C15	Improve FLIR condition forecasting techniques	Materiel	VLow
AH64-C16	Enhance risk management training	Training	Low
AH64-C17	Envelope cueing (exceedances).	Materiel	Medium
AH64-C18	Digital source collector and develop procedures for use of FDR data by commanders for aircrew training	Materiel	Medium
AH64-C19	Develop tools to help commanders identify high risk behavior	Ldr Dev	
AH64-C20	Modifying flight symbology (VSI)	Materiel	Low
AH64-C21	Digital Source Collector (DSC) and envelope cueing (exceedences) and notice to pilot of exceedences/crew monitor	Materiel	High
AH64-C22	Improve PNVS	Materiel	High
AH64-C23	Flight Symbology (velocity vector & VSI) overlay on TADS	Materiel	Low
AH64-C24	Standards or guidance for risk assessment articulation for cummulative risk	Doctrine	VLow
AH64-C25	Make an evaluation task (hovering in close prox to terrain, degraded visual environment, and high work-load)*** DES Clarification	Training	VLow
AH64-C26	Family of controls for vision enhancement systems	Materiel	
AH64-C27	Integrate improved night vision goggle system and training for CPG	Materiel	Low
AH64-C28	Fence existing flying hour dollars	Training	Nil
AH64-C29	Standardize use of ERFS (restrict for theater self deployment - including train ups - or ferry missions only) through doctrinal change	Doctrine	Nil
AH64-C30	Acquire crashworthy ERFS	Materiel	
AH64-C31	Communicate HQDA acceptance of risk for current use of ERFS	Org	Nil

CONTROL	CONTROL STATEMENT	DTLOMS	COST
AH64-C32	Install fire detection and suppression in T-back area to include the forward area	Materiel	Medium
AH64-C33	Install new APU clutch w/ disengage feature (one-way).	Materiel	Medium
AH64-C34	Develop new anti-flail containment for APU drive shaft.	Materiel	Low
AH64-C35	Integrate new anti-flail containment for APU drive shaft into Drive train 2000	Materiel	Nil
AH64-C36	Integrate new APU clutch w/ disengage feature (one-way) into Drive train 2000	Materiel	Low
AH64-C37	Redesign APU clutch	Materiel	Medium
AH64-C38	Mandatory replacement with new yellow harness	Materiel	VLow
AH64-C39	Establish requirement for emergency procedure training for single engine failure in the Combat Mission Simulator (Increase awareness of high side or low side failures)	Training	Nil
AH64-C40	Increase & improve data captured for Class C accidents through the use of DA 2397 forms	Org	VLow
AH64-C41	Shroud tail-rotor	Materiel	High
AH64-C42	Standardize doctrine and operational procedures for mulit-ship operations involving mixed night vision systems, including associated training (flight and simulator)	Doctrine	Medium
AH64-C43	Defer to USAALS to look at maintenance related controls to reduce FOD hazards associated with tools	Org	VLow
AH64-C44	Defer to USAALS to look at maintenance related controls to reduce hazards associated with maintenance discipline	Org	VLow

CONTROL	CONTROL STATEMENT	DTLOMS	COST
AH64-C45	Increase damage tolerance of aircraft	Materiel	High
AH64-C46	Emphase proper pilot reaction to impending bird strike (maintain steady flight)	Training	VLow
AH64-C47	Cockpit indication of component security	Materiel	Medium
AH64-C48	Value engineering study of fasteners	Materiel	VLow
AH64-C49	Safety Latch (mechanical secondary latch for the tail rotor driveshaft cover)	Materiel	Low
AH64-C50	Establish improved technique (as part of preflight) to physically ensure integrity of cowlings	Training	Nil
AH64-C51	Redesign/upgrade of latching devices	Materiel	Low
AH64-C52	Require correct size cam locks be installed in each application	Training	Nil
AH64-C53	USAALS evaluate possible elimination of multiple size cam locks	Materiel	VLow
AH64-C54	Paint leading edge of engine cowling day glow orange	Materiel	Nil
AH64-C55	Book of Hazards and Controls	Training	VLow
AH64-C56	Establish a command information system which tracks all forms of high risk behavior and marginal performance	Materiel	Low
AH64-C57	Modify AR 95-3 to require that mission planning time is considered as mandatory topic for risk determination and establish risk management standards for mission planning time	Ldr Dev	Nil
AH64-C58	Integrate risk management training into aviation officer/WO/NCO development programs (use accident experience as part of the training)	Org	Low
AH64-C59	Develop a standardized methodology for conducting mission risk assessments with the objective for identification of all hazards and associated controls to be presented in the mission brief	Training	VLow

CONTROL	CONTROL STATEMENT	DTLOMS	COST
AH64-C60	Establish model RM training program, starting with DAIG evaluation of all institutional training schools for integration of risk management training into curriculum	Training	VLow
AH64-C61	Establish minimum training requirements (concerning seleced enforcement of aviation maintenance and operations standards) for assignment as commanders (integration into advanced course, an exportable training package, and modifying BOC and AOC)	Training	VLow
AH64-C62	Establish or enforce selection criteria for advanced aviator training	Training	VLow
AH64-C63	Increase command emphasis (Advance Course) on safety incentives	Training	VLow
AH64-C64	Evaluate AH-64 maintenance force structure.	Org	VLow
AH64-C65	Provide an effective back-up control system (no transients, redundancy, transparent -equivalent control feel and response)	Materiel	High
AH64-C66	Reactivate BUCS	Materiel	Medium
AH64-C67	Remove BUCS (Consider Red Team for mishap data and effectiveness rating)	Materiel	Low
AH64-C68	Redesign primary flight control system to military specification (redundancy, ballistic tolerance, and strength requirement)	Materiel	High
AH64-C69	Reactivate BUCS in pre PV 529 aircraft and AH64D lot 1 a/c	Materiel	Low
AH64-C70	Re-orient direction of swage pin	Materiel	VLow
AH64-C71	Redesign tail rotor control to provide fixed medium pitch setting equivalent to nominal thrust to transition to controlled flight and controlled landing (rewrite -10 for new emergency procedure)	Materiel	Medium

CONTROL	CONTROL STATEMENT	DTLOMS	COST
AH64-C72	Install a new design strap pack with an established service life	Materiel	Medium
AH64-C73	Revise and enforce government oversight procedures (AR 95-20)	Materiel	VLow
AH64-C74	Revise -23 with new NDI inspection and procedures	Materiel	VLow
AH64-C75	Redesign refuel nozzle to include visual locking indication	Materiel	Low
AH64-C76	Increase emphasis on assembly of refueling equipment and hot refueling during POL operator training (initial training and new requirement for recurring qualification training and annual recertification)	Training	Low
AH64-C77	Provide Personal Protective Equipment to POL handlers	Materiel	Low
AH64-C78	Install cockpit airbag system	Materiel	High
AH64-C79	Install MA-16 inertia reels	Materiel	VLow
AH64-C80	Cooler search light bulb	Materiel	Low
AH64-C81	Install heat shield for search light	Materiel	Low
AH64-C82	Add a light on the caution advisory panel to indicate search light condition (on/off)	Materiel	Low
AH64-C83	Install Flight Data Recorder	Materiel	Medium
AH64-C84	Pressurize cockpit to redirect airflow out of the cockpit	Materiel	Medium
AH64-C86	Redesign internal fuel system (baffled system)	Materiel	Medium
AH64-C87	Install air tolerant fuel pump (bubble eating pump)	Materiel	Medium
AH64-C88	Redesign fuel transfer system to a fuel suction system	Materiel	Medium
AH64-C89	Install automatic external fuel transfer shutoff prior to ingestion of air	Materiel	Medium
AH64-C90	Install automatic fuel management system (including management of aux fuel)	Materiel	Medium
AH64-C92	Obstacle detection system	Materiel	Medium

CONTROL	CONTROL STATEMENT	DTLOMS	COST
AH64-C94	Establish lot accept testing controls for aircraft ordnance	Materiel	Low
AH64-C95	Command emphasis campaign from HQDA(CSA), Aviation Branch Chief, and Aviation principals to enforce standards	Ldr Dev	VLow
AH64-C96	Study and establish minimum operational experience and flight time requirements for selection as aviation commander	Ldr Dev	Low
AH64-C97	Provide training through Pre-command Course to increase awareness of need for Bn Commander to broaden junior officer development - management of flying hour program and risk management	Ldr Dev	VLow

C.2 Control List for the H-47 Chinook

CONTROL	CONTROL STATEMENT	DTLOMS	COST
H47-C01	Enhanced risk management training at all levels of command	Training	VLow
H47-C02	Obstacle collision warning system which includes provisions for PI-adjustable parameters.	Materiel	Medium
H47-C03	Increase pilot flight hours and supervision	Training	Medium
H47-C04	Digital source collector and develop procedure for use of DSC data by commanders for aircrew training.	Materiel	Medium
H47-C05	WSPS	Materiel	Medium
H47-C06	Crew coordination sustainment training	Training	Low
H47-C07	Back-up DC (battery)-powered IMC instruments	Materiel	Low
H47-C08	Install state-of-the-art waterproof circuit breaker	Materiel	Low
H47-C09	Seal fuselage to prevent water intrusion	Materiel	VLow
H47-C10	Redesign fuselage to prevent water intrusion	Materiel	High

CONTROL	CONTROL STATEMENT	DTLOMS	COST
H47-C11	Increase manning levels to match present operations in aviation units, considering non-aviation requirements	Soldiers	High
H47-C12	Develop and provide training to commanders to match crew experience with mission requirements to include risk management training	Training	Low
H47-C13	Reverify 240-23 flight control hardware installlation against H-47D production drawings	Materiel	VLow
H47-C14	Training for CCAD personnel in CH-47-peculiar maintenance practices	Materiel	VLow
H47-C15	Increase technical oversight of the maintenance manual (increase personnel)	Org	Low
H47-C16	Increase PEO/PM/AMCOM system dedicated field representation to provide technical oversight and operational feedback.	Org	Low
H47-C17	Add ground proximity (squat) switches to forward landing gear which limits responsiveness of control input	Materiel	Low
H47-C18	add warning to dash 10 for limits on upslope landing to include adding forward cyclic while on upslope	Training	Nil
H47-C19	Develop risk assessment procedure for waivers to AR 95-1 requirements. Process Issue: Need to change waiver process into a risk management process	Doctrine	VLow
H47-C20	Standardize cargo release operations, with a change to the ATM, mandating use of hot mike during external operations whenever master cargo hook is activated.	Training	Nil
H47-C21	improved design of cargo release switch	Materiel	Low
H47-C22	Modify AR 95-1 to mandate seatbelt usage when not performing flight crew duties. (may apply to other aircraft)	Training	Nil

CONTROL	CONTROL STATEMENT	DTLOMS	COST
H47-C23	Change phase maintenance manual requiring bench test of AFCS computer at phase.	Materiel	VLow
H47-C24	Modify -23 to establish TBO for integrated lower control actuators (ILCAs) and review adequacy of upper boost actuators (UBAs) TBO	Materiel	Low
H47-C25	Develop emergency procedure for flight control lockup	Training	VLow
H47-C26	Modify flight control system to provide inflight indication of Integrated Lower Control Actuator (ILCA) and Upper Boost Actuator (UBA) jams	Materiel	High
H47-C27	Develop and implement new Army Oil Analysis Program (AOAP) procedure for hydraulic fluid analysis	Materiel	Low
H47-C28	Develop new standards to increase number of fastrope crew members for missions	Org	Nil
H47-C29	Redesign HAR refeuling probe	Materiel	High
H47-C30	Change SOP responsibility for search light controls to flight engineer	Training	Nil
H47-C31	Develop and train HAR refueling scenerio in a high fidelity simulatior	Mat/Trg	Low
H47-C32	Improve tanker cueing	Materiel	Medium
H47-C33	Install day and night remote viewing devices to view cargo hook operations	Materiel	Low
H47-C34	4 axis hover hold	Materiel	Medium
H47-C35	Install winchable hook assemblies	Materiel	High
H47-C36	Modify -10 to mandate 4th crew member for sling load operations	Soldiers	Low
H47-C37	automated approach landing system (improved FCS)	Materiel	Medium
H47-C38	Information system to provide realtime weather at unit operations	Materiel	VLow
H47-C39	Second generation FLIR	Materiel	High

CONTROL	CONTROL STATEMENT	DTLOMS	COST
H47-C40	update ATM TC1-216 to include landing procedures for various terrain	Training	Nil
H47-C41	Mandate a regulatory requirement to ensure airfields are marked IAW TM 5-803-4 and deviations published in FLIP.	Doctrine	Nil
H47-C42	Modify appropriate TM to require marking of all potential hazards/obstacles.	Doctrine	Nil
H47-C43	Modify MOS program for 67U to include academic/practical training for ground guide/wing walker responsibilities.	Training	VLow
H47-C44	Pre-mission briefing of all expected hazards and controls to be used.	Doctrine	Nil
H47-C45	audio volume control on low altitude warning	Materiel	VLow
H47-C46	terrain avoidance radar (coupled into FCS)	Materiel	High
H47-C47	Reinstitute ATM Task 1078 (Unusual Attitude Recovery) for VMC	Materiel	High
H47-C48	Develop an emergency flight control response limiter	Materiel	High
H47-C49	improved NVG	Materiel	Low
H47-C50	Increase information recorded on accident forms, use DA-2397 series forms.	Doctrine	VLow
H47-C51	Command emphasis	Ldr Dev	Nil
H47-C52	Develop a better debris detection system using "full-flow" technology.	Materiel	Low
H47-C53	Develop a mean or reporting deployability status of mission equipment (ERFS)	Training	VLow
H47-C54	Change location of N2 speed feedback assembly	Materiel	Medium
H47-C55	Accident scenarios in simulator	Training	Nil
H47-C56	Design provisions for protective stowage of the cargo release switch	Materiel	Low

CONTROL	CONTROL STATEMENT	DTLOMS	COST
H47-C57	Install DSC in all H-47	Materiel	Medium
H47-C58	Improve existing non-slip surface	Materiel	Nil
H47-C59	"dead man" ramp control switch	Materiel	VLow
H47-C60	Accelerate installation of ECP D229	Materiel	Low
H47-C61	accelerate installation of MWO 55-1520-240-50-52 combat lighting	Materiel	Low
H47-C62	accelerate installation of the collector gear cartridge ECP	Materiel	Medium
H47-C63	Accelerate installation of the older style (-5) fan shaft	Materiel	Medium
H47-C64	ASAM-99-02	Materiel	Nil
H47-C65	Better troubleshooting procedures	Training	VLow
H47-C66	Clarify SOPs (Ranger vs. 160th)	Training	Nil
H47-C67	Clear crew coordination	Training	Nil
H47-C68	Combat engineers survey and maintain areas for flight operations	Org	High
H47-C69	Communication plan (Ship to ground as well as ship to ship)	Training	Nil
H47-C70	Complete with an adequate MWO to address the spirit of the Boeing bulletin	Materiel	Low
H47-C72	Crew and Pax briefings	Training	Nil
H47-C73	cross training of Crewchiefs and Fast-Rope Safeties	Training	Nil
H47-C74	Develop a quick and easy reference to develop LZ sizes for diferent aircraft	Training	Nil
H47-C75	Develop a wear indicator gage	Materiel	Low
H47-C76	Develop crew member emergency procedure training in simulator	Training	VLow
H47-C77	Develop FE/CE requirement in TC 1-216 to obtain PI clearance to lower ramp after landing.	Training	Nil

CONTROL	CONTROL STATEMENT	DTLOMS	COST
H47-C78	Develop policies and procedures for weather risk management decisions through unit operations center (to include maintenance operations)	Training	VLow
H47-C79	Develop procedure to track maintenance trends	Doctrine	Nil
H47-C80	Emergency procedure standardization during maintenance test flights.	Training	Nil
H47-C81	Enhance communication between Fast Rope Master and Safety	Training	Nil
H47-C82	Enhance crew coordination (call out for arming and alert caution to release button) with caution box in the ATM	Materiel	Nil
H47-C83	Ensure chip detector design and location is appropriate to indicate presence of metal particles in the oil	Materiel	Low
H47-C84	Establish a maintenance FE position for maintenance test flights	Soldiers	Medium
H47-C85	Establish overhaul interval for APU	Materiel	Medium
H47-C86	Etching on the striker plate to provide indication of wear	Materiel	Low
H47-C87	Folding rotor system (SH-60)	Materiel	High
H47-C89	harnesses for flight engineers to help with leverage	Materiel	Medium
H47-C90	Highlight striker plate wear as an emphasis item in preflight	Training	Nil
H47-C91	Identify and track special classification for potentially hazardous conditions	Training	N/A
H47-C92	Improve avionics door latch	Materiel	Low
H47-C93	Improve crew coordination/planning for emergency situations	Training	Nil

CONTROL	CONTROL STATEMENT	DTLOMS	COST
H47-C94	Improve handling characteristics at high speed flight by providing means to fine tune speed management or improve AFCS	Materiel	High
H47-C95	Improve NVD (field of view and visual acuity) to help identify closure rates	Materiel	High
H47-C96	Improve understanding and confidence in navigaion equipment	Training	Nil
H47-C97	improve winch to perform ingress assistance of individual	Materiel	Medium
H47-C99	Incorporate tools in the Risk Management process for accountability of the increased risk due to lack of funding.	Ldr Dev	Nil
H47-C100	Increase available funding for safety ECPs	Materiel	High
H47-C101	Increase awareness on the ground commander to anticipate requirements for LZ	Training	Nil
H47-C102	Increase emphasis on emergency procedures	Training	Nil
H47-C103	Increase oil capacity	Materiel	Medium
H47-C104	Information system to provide realtime weather at unit operations	Materiel	Low
H47-C105	Install a backup oil cooling system	Materiel	Medium
H47-C106	Install containment ring around APU	Materiel	Low
H47-C107	Install DSC and HUMS to capture data	Materiel	Medium
H47-C108	Onboard weather avoidance equipment to facilitate identification of storm cells during flight	Materiel	Low
H47-C109	Install DSC to capture data to use in clutch performance and TBO determination analysis	Materiel	High
H47-C110	Install FADEC	Materiel	High
H47-C111	Install HUMS	Materiel	Medium

CONTROL	CONTROL STATEMENT	DTLOMS	COST
H47-C112	Install increased de-icing capability on all H-47s	Materiel	High
H47-C113	Install new compressor wheels in APU	Materiel	Low
H47-C114	Limit number of winch lift cycles to minimize injury risk	Training	Nil
H47-C115	Load sensor to detect load on ground to allow crew chief to release load (this control also requires movement of emergency release button and enhanced emergency procedures)	Materiel	High
H47-C116	mandate use of metal clevis to reach pendant	Materiel	Nil
H47-C117	Mandatory retrofit of -11 lag dampener	Materiel	Low
H47-C118	Match personnel physical standards with task requirements	Organization	Nil
H47-C119	Match personnel to mission requirement according to SOP	Soldiers	Nil
H47-C120	Modify aircraft to provide greater crew visibility directly beneath the aircraft	Materiel	Low
H47-C121	Night Vision Devices for FAST Rope Masters and Safeties	Training	Nil
H47-C122	Provide aircrew training on ground resonance	Training	Nil
H47-C123	Provide standardized configuration for securing winch/hoist control grip assembly during external load operations	Training	Nil
H47-C124	reconfigure load (remove blades)	Training	Nil
H47-C125	Redesign engine control system to prevent rotor overspeed.	Materiel	High

CONTROL	CONTROL STATEMENT	DTLOMS	COST
H47-C126	Redesign latch to meet operational loads and vibrations	Materiel	Low
H47-C127	Redesign the transmission and oil cooling system	Materiel	High
H47-C129	Remote wireless ramp control	Materiel	Medium
H47-C130	Research new procedures and methods for flight control hydraulic system inspections/maintenance on recurring basis	Materiel	Low
H47-C131	Operational Risk Management enhancements	Training	VLow
H47-C132	Safety-of-Flight to remove APUs past xxx hrs.	Materiel	Medium
H47-C133	Separate funding from the decision making process	Materiel	Nil
H47-C134	Smart drogue to detect fuel line tension and safely maintain engagement	Materiel	Medium
H47-C136	Symposium or other forums with USAF/USA to highlight division of tasks/hazards/risks/controls associated with HAR	Training	VLow
H47-C137	Update TC 1-216 to focus on crew member communication skills	Training	Nil
H47-C138	use of high temperature tolerant materials	Materiel	N/A
H47-C139	voice activated communication system	Materiel	Medium
H47-C140	Provide training through Pre-command Course to increase awareness of need for Bn Commander to broaden junior officer development - management of flying hour program and risk management	Ldr Dev	VLow
H47-C141	Study and establish minimum operational experience and flight time requirements for selection as aviation commander	Ldr Dev	Low
H47-C142	Command emphasis campaign from HQDA(CSA), Aviation Branch Chief, and Aviation principals to enforce standards	Ldr Dev	VLow

C.3 Control List for the OH-58D Kiowa Warrior

CONTROL	CONTROL STATEMENT	DTLOMS	COST
OH58-C01	Relocate CSC to improve visibility/accessibility	Materiel	Low
OH58-C02	Field the improved CSC (voice activated) throughout the fleet to eliminate requirement	Materiel	Low
OH58-C03	Improved Flight Control System (FCS) - Attitude Command Attitude Hold (ACAH) + Hover Hold	Materiel	Medium
OH58-C04	Obstacle warning device that identifies direction of obstacles (virtual rotor disc)	Materiel	Medium
OH58-C05	Digital Source Collector (DSC)/Voice recorder	Materiel	Medium
OH58-C06	Provide pilot capability to focus outside for all tasks (Day/night/NVG HUD with weapons and flight symbology)	Materiel	Medium
OH58-C07	Articulated weapons pylons	Materiel	High
OH58-C08	Improved ANVIS resolution, acuity, and FOV	Materiel	Low
OH58-C09	Crew coordination sustainment training	Training	Low
OH58-C10	Field a high fidelity simulator and develop accident avoidance scinerio for simulator training	Materiel	High
OH58-C11	Enhance risk management policy to provide feedback for reassessments to commander/decision maker as conditions change	Ldr Dev	VLow
OH58-C12	Increase aircrew experience (flying hour program and increase proficiency minimums) - increase avg exp from 400 hr to 1000 hr	Org	High
OH58-C13	Redesign/standardize fuel hose coupling	Materiel	Low
OH58-C14	Improve qualification (MOS) and unit training on all aviation refueling equipment (USAALS coordination)	Training	VLow
OH58-C15	Establish DA program to procure and manage standardized fueling equipment (need to research proponent)	Materiel	Low

CONTROL	CONTROL STATEMENT	DTLOMS	COST
OH58-C16	Establish standard in the -10 to disable flight controls when the crew station is occupied by non-rated passenger	Doctrine	Nil
OH58-C17	Develop and field a wire/obstacle detection system	Materiel	Medium
OH58-C18	Add an audio warning to provide a throttle warning at 400 feet with throttle at idle	Materiel	Medium
OH58-C20	Improve autorotational characteristics/sink rate	Materiel	High
OH58-C21	Establish a minimum entry altitude for initiation of a simulated engine failure	Doct/Trg	Nil
OH58-C22	Enhance crew coordination task (requiring PI to confirm IP has rolled throttle on-check throttle)	Training	Nil
OH58-C23	Increase SEF training(both AQC, IPC/MOI, and unit training)	Training	Low
OH58-C24	Modify the ATM to make the SEF task a mandatory part of the mission briefing	Training	Nil
OH58-C26	Make landing gear and attachment points more tolerant to hard landings	Materiel	Medium
OH58-C27	Increase SEF/Autorotation training(both AQC, IPC/MOI, and unit training)	Training	Low
OH58-C29	Materiel modification already applied	Materiel	Zero
OH58-C30	Enforce maintenance standards with command emphasis	Ldr Dev	Nil
OH58-C31	Fill the OH-58D maintenance force structure (coordinate with USAALS/PERSCOM)	Soldiers	Low
OH58-C33	Incorporate FADEC fleetwide	Materiel	High
OH58-C34	Include hazards and controls in MOI flight training guide	Training	Nil
OH58-C35	Enforce procedures with command emphasis	Ldr Dev	Nil

CONTROL	CONTROL STATEMENT	DTLOMS	COST
OH58-C36	Modify Fighter Management Procedures to include maintenance personnel	Ldr Dev	Nil
OH58-C37	Information system to provide realtime weather at unit operations (DTN, WSI, NOAA, DUATS)	Materiel	Low
OH58-C38	Improved aircraft weather detection system	Materiel	High
OH58-C39	Increase power and torque available	Materiel	High
OH58-C40	Install collective soft stop (tactile cueing to provide overtorque feedback to pilot), including incident reconstruction capability	Materiel	Medium
OH58-C41	Install flight envelop cueing, including incident reconstruction capability	Materiel	Medium
OH58-C42	Ensure retrofit of crashworthy seats is applied to all aircraft	Materiel	Medium
OH58-C43	Equip left seat collective with RPM trim switch, search light on-off, and search light control	Materiel	Medium
OH58-C44	Accelerate ECP application	Materiel	Low
OH58-C45	Design a reliable fire detection and suppression system	Materiel	Medium
OH58-C46	Remove SCAS switch from cyclic	Materiel	High
OH58-C47	Resourcing of thermal protective equipment for all 77F's	Materiel	Medium
OH58-C48	Strengthen Optical Display Assembly training (both AQC and unit training)	Training	Low
OH58-C49	Increase minimum hover altitude in unit SOP to 10 feet for operating on rolling ships	Training	Nil
OH58-C50	Identify object strike hazards effecting hovering altitudes during orientations, reconnaissances and premission planning for incorporation into unit SOPs and premission brefings.	Training	Nil
OH58-C51	Enforce existing standards and controls	Ldr Dev	Nil
OH58-C52	Change ATM to define height/altitude restriction	Training	VLow

CONTROL	CONTROL STATEMENT	DTLOMS	COST
OH58-C53	Ensure proper marking of and notification of potential hazards is provided to aircrews and updated as necessary during flight operations	Ldr Dev	Nil
OH58-C54	Restrict aircaft flight operations in periods of marginal weather to those necessary to complete the mission	Ldr Dev	Nil
OH58-C55	Include appropriate markings to indicate aircraft is undergoing maintenance	Doct/Trg	VLow
OH58-C56	Ensure proper IP supervision of students	Training	Nil
OH58-C57	Ensure objects in proximity of aircraft (inside of ballistic barriers) are properly secured	Ldr Dev	VLow
OH58-C58	Inform aircrew of hazards associated with not using provided eye protection (visor)	Training	Nil
OH58-C59	Ensure aviation unit maintenance personnel are aware of the QDR program by conductiing initial and recurring training	Training	Nil
OH58-C60	Ensure SOPs and policies for precautionary landings at Ft Rucker are reviewed and understood by Ft Rucker personnel.	Training	VLow
OH58-C61	Ensure information on engine fuel control operation during engine starts (including degraded modes of operation) is provided in the operator's manual.	Training	VLow
OH58-C62	Ensure complete information is incorporated in the operator's manual addressing cyclic lock-out	Training	Nil
OH58-C63	Verify communications prior to flight	Training	Nil
OH58-C64	Develop hover training progression to progress to standard	Training	Nil
OH58-C65	Warning to inform pilots to hover into the wind in the event of an emergency	Training	Nil
OH58-C66	Command emphasis	Ldr Dev	Nil

CONTROL	CONTROL STATEMENT	DTLOMS	COST
OH58-C67	Instill self discipline	Ldr Dev	Nil
OH58-C68	Authorized personnel and authorized tools	Org	Low
OH58-C69	Warnings in technical manuals	Training	Low
OH58-C70	Closer attention to flight by tower personnel/TSO	Training	Nil
OH58-C72	Emphasize PPE through existing force protection	Ldr Dev	Nil
OH58-C73	Provide training on standardized fire supression systems for tactical FARP operations	Training	Nil
OH58-C74	Changes to unit SOP for shutdown and post flight inspections after conducting emergency procedures training.	Training	Nil
OH58-C75	Incorporate changes to -10 to highlight upstop conditions	Training	Low
OH58-C76	Education of effects of moisture/ dew point	Training	Nil
OH58-C77	Research Center for Army Lessons Learned for operational risk management information	Ldr Dev	Nil
OH58-C78	Increase frequency of wire replacement	Doctrine	Nil
OH58-C79	Modify WSPS to preclude wire cutter contact with ground during A/R landings	Materiel	Low
OH58-C80	Provide training through Pre-command Course to increase awareness of need for Bn Commander to broaden junior officer development - management of flying hour program and risk management	Ldr Dev	VLow
OH58-C81	Study and establish minimum operational experience and flight time requirements for selection as aviation commander	Ldr Dev	VLow
OH58-C82	Command emphasis campaign from HQDA(CSA), Aviation Branch Chief, and Aviation principals to enforce standards	Ldr Dev	VLow

C.4 Control List for the UH-60 Black Hawk

CONTROL	CONTROL STATEMENT	DTLOMS	COST
H60-C01	Add mandatory scenario training in simulator (emergency procedures, power management, brownout) to include resourcing of TDY	Org	Low
H60-C02	Book of hazards and controls	Soldier	VLow
H60-C03	Change ATM to establish new flying hour category for individual task flight training hours (not collective training)* and resource individual training.	Doctrine	Low
H60-C04	Develop external crashworthy fuel tanks consider suction fuel system	Materiel	Medium
H60-C05	Establish a command information system which tracks all forms of high risk behavior and marginal performance	Ldr Dev	Low
H60-C06	Establish and sustain crewchief's "school house" training program	Training	Low
H60-C07	Establish crew coordination sustainment program	Training	Low
H60-C08	Establish standards for and resource a 4th crewmember for high workload (mulit-ship, night) operations. Include in mission planning/briefs/assessment.	Org	Medium
H60-C09	Expand AQC training (emergency procedures/emergency diagnosis, mulitship operations, and flight limitations)	Training	Low
H60-C10	Implement a change to the flight control system to improve aircraft stability and control in low speed flight (Attitude Command Attitude Hold)	Materiel	Medium
H60-C11	Increase the available aircrew experience.	Org	High
H60-C12	quirement to highlight specific controls during the air mission brief.	Ldr Dev	Nil

CONTROL	CONTROL STATEMENT	DTLOMS	COST
H60-C13	Provide commanders a better ability for selection, mission tailoring, and balancing of resources to do the mission	Ldr Dev	Low
H60-C14	Develop a wire strike protection system that covers more of the aircraft	Materiel	Medium
H60-C15	Enhance NVG field of view	Materiel	Medium
H60-C16	Develop and field a proximity warning system (Virtual Rotor Disk)	Materiel	Medium
H60-C17	Fund and install flight data recorder (FDR) for accident and incident investigation.	Materiel	Low
H60-C18	Increase command emphasis (Advance Course) on safety incentives	Training	VLow
H60-C19	Modify AR 95-3 or TC 1-210 to require 2 hours annually of actual instruments for each PIC	Training	VLow
H60-C20	Develop and field an adjustable proximity warning system/collision avoidance.	Materiel	High
H60-C21	Develop a terrain following / terrain avoidance radar	Materiel	High
H60-C22	Develop standardized training support package for use at unit level targeted on ERFS operations to include simulator scenario training, jettison stores, a/c performance characteristics	Materiel	VLow
H60-C23	Manual changes to describe handling characteristics	Materiel	VLow
H60-C24	Develop and install new Night Vision Systems	Materiel	Medium
H60-C25	Improve aircraft controllability with tanks installed (pitch bias actuator, digital stabilator amp)	Materiel	Low
H60-C26	Improve IFR/IMC infrastructure in selected parts of the world (ABSO define)	Materiel	High
H60-C27	Wire detection system using laser radar or HF radar technology	Materiel	High

CONTROL	CONTROL STATEMENT	DTLOMS	COST
H60-C28	Resource aviation maintenance IAW reference XYX to match requirements of complex aircraft. (link to US-AALS needed to consider dedicated crews to aircraft)	Materiel	High
H60-C29	Full authority DEC automatically causes engine shut-down	Materiel	High
H60-C30	Improve engine diagnostics and improve cueing of correlation of PCL handle to engine	Materiel	Medium
H60-C31	Accelerate addressing materiel failures	Materiel	High
H60-C32	Improve crew's ability to for premission planning by implementing electronic data management from Air Warrior	Materiel	Medium
H60-C33	Enforce rules through leadership commitment	Ldr Dev	VLow
H60-C34	Digital Source Collector (DSC) and envelope cueing (exceedences) and notice to pilot of exceedences/crew monitor	Materiel	High
H60-C35	Increase minimum distance between aircraft for multiship operations	Doctrine	Nil
H60-C36	Modify manual to establish method of calculating lateral CG	Materiel	Low
H60-C37	DAIG evaluate all institutional training schools for integration of risk management training into curriculum.	Training	Low
H60-C38	Establish or enforce selection criteria for advanced aviator training	Org	VLow
H60-C40	Develop a standardized methodology for conducting mission risk assessments with the objective for identification of all hazards and associated controls to be presented in the mission brief	Ldr Dev	Low

CONTROL	CONTROL STATEMENT	DTLOMS	COST
H60-C41	Evaluate system specific instruction in the UH-60 IP course. Emphasize what system specific instruction is imparted by IP's to other aviators during assignments (effectiveness is N/A)	Training	Low
H60-C42	Expand leader development training to emphasize enforcement of aviation maintenance and operations standards (integration into advanced course, an exportable training package, and modifying BOC and AOC)	Ldr Dev	Low
H60-C43	Integrate risk management training into aviation officer/WO/NCO development programs (use accident experience as part of the training)	Ldr Dev	Low
H60-C44	Install Flight Data Recorders (FDRs) and develop procedures for use of FDR data by commanders for aircrew training	Materiel	Low
H60-C45	Evaluate H-60 maintenance force structure (effectiveness is N/A)	Org	N/A
H60-C46	Investigate improving H-60 handling qualities by implementing strakes to improve airflow over the tailboom (N/A effectiveness)	Materiel	Low
H60-C47	Develop a smooth deflection device on top of ALQ-144	Materiel	Low
H60-C48	Relocate /redesign ALQ-144 (substitute ATIRCMS)	Materiel	Low
H60-C49	Develop and distribute an exportable training package for unit level Aviation refuelers and mandate training requirement prior to assignment as aviation refueler	Training	Low

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14. ABSTRACT

The Army is concerned with maintaining safe operations in light of increasing operational demands. The Army Safety Center's goal, as approved by the Under Secretary of Defense for Acquisitions and Technology, is to reduce accident severity by 50% in the next decade. The Safety Center chartered the Aviation Safety Investment Strategy Team to evaluate accidents to determine their hazards, or contributing conditions, and their controls, or reduction measures. This study specifically targets the force-modernized aircraft, AH-64 Apache, CH/MH-47 Chinook, OH-58D Kiowa Warrior, and UH-60 Black Hawk.

This research takes a look at selecting the best portfolios of controls to minimize aviation accident severity. The accidents are simulated using Monte Carlo techniques. Value-Focused Thinking techniques evaluate the severity of accidents generated by the simulation. The optimization is approached using a knapsack heuristic. Insights into selecting the best sets of controls aid decision makers when determining the portfolios with the best Percent Severity Reduction given budget considerations.

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